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A TECHNOLOGY REVIEW OF PARTICLE REMOVAL BY WATER FILTRATION

A Technology Review of Particle Removal by Water Filtration

Prepared by:

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Prepared for:

Alberta Environment
Municipal Engineering Branch
Standards and Approvals Division

August, 1985

Acknowledgements

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ATTENTION: Mr. David Spink, M.Sc., P. Eng.
Branch Head, Municipal Engineering

Dear Sir:

RE: TECHNOLOGY REVIEW: PARTICLE REMOVAL
BY WATER FILTRATION

We are pleased to submit herewith the above noted report.

We thank you for the opportunity to conduct the review, and would be pleased to discuss it with you in further detail.

Yours truly,

UNDERWOOD McLELLAN LTD.

P.W. Given

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1. SUMMARY

The following report examines water filtration technologies and the factors affecting their ability to remove particles from raw water supplies. The performance of granular media filters is reviewed in terms of filter configurations, operating modes, filter media characteristics, and influent particle characteristics. Relevant mathematical models and computer applications are also reviewed. More than 150 articles were reviewed in the process of preparing this report. The reviewed literature represents a comprehensive cross-section of research and operating experience with respect to water filtration technologies and particle removal.

Table 1 summarizes pertinent design and operating informaton on the four main types of water filtration processes used today. All can achieve high performance levels (> 99% removal of particles) provided they are designed and operated properly. Review of operational data from pilot plant studies or existing facilities is a necessary part of the design process. Also, the data can provide a means of predicting performance in an operating facility using computer simulations or parallel pilot plants. This is important where fluctuations in raw water quality are known to occur and it is desirable to alter the plant operation to maintain high quality finished water.

The accurate assessment of raw water quality in terms of particle size and distribution is considered important in the proper design of a water treatment plant. The interdependence of coagulation, flocculation, sedimentation and filtration requires

Table 1. Summary of downflow filtration technologies. (after Fair et al.[84])

	Slow Sand Filters	Rapid Sand Filters	Multi-Media Filters	Precoat Filters
Rate of filtration	0.04 to 0.42 m/h	4.0 to 13.0 m/h	4.8 to 24 m/h	0.5 to 16 m/h
Size of bed	Large, 2000 m^2	Small, 40 to 400 m^2	Small	Small
Depth of bed	300 mm of gravel; 1.1 m of sand, usually reduced to no less than 600 mm by scraping	450 mm of gravel; 750 mm of sand, or less; not reduced by washing	Varies, see Table 8	12 to 40 mm
Size of media	Effective size 0.25 to 0.35 mm; coefficient of uniformity <2 to 3	0.45 mm and higher; coefficient of uniformity 1.5 and lower, depending on underdrainage system	Varies, see Table 8	0.5 to 12 mm
Grain size distribution of sand in filter	Unstratified	Stratified with smallest or lightest grains at top and coarsest or heaviest at bottom	Reverse of rapid sand filter	Unstratified
Underdrainage system	Split tile laterals laid in coarse stone and discharging into main drains	(1) Perforated pipe laterals discharging into pipe mains; (2) porous plates above inlet box; (3) porous blocks with included channels	Same as rapid sand filter	N/A
Loss of head	0.06 m initial to 1.2 m final	0.3 m initial to 2.5 m final	Same as rapid sand filter	2.4 m initial to 14 m final
Length of run between cleanings	20 to 60 d	12 to 72 h	Same as rapid sand	24 to 120 h
Penetration of suspended matter	Superficial	Deep	Deep	Superficial, rising with body feed
Method of Cleaning	(1) Scraping off surface layer of sand and washing and storing clean sand for periodic resanding of bed; (2) washing surface sand in place by washer traveling over sand bed	Dislodging and removing suspended matter by upward flow or backwashing, which fluidizes the bed. Possible use of water or air jets, or mechanical rakes to improve scour	Same as rapid sand filter	Backwash to remove precoat and discharge to waste
Amount of wash water used in cleaning sand	0.2 to 0.6% of water filtered	1 to 6% of water filtered	3 to 5% of water filtered	N/A
Preparatory treatment of water	Generally none	Coagulation, flocculation, and sedimentation	Same as rapid sand filter	Generally none
Supplementary treatment of water	Disinfection	Disinfection	Disinfection	Disinfection
Cost of construction, U.S.A.	Relatively high	Relatively low	Relatively low	Relatively high
Cost of operation	Relatively low where sand is cleaned in place	Relatively high	Relatively high	Relatively high
Depreciation cost	Relatively low	Relatively high	Relatively high	Relatively high

a uniform basis of modelling performance which uses particle counts and size distributions. Each process can be modelled if adequate information is given describing the raw water in terms of particle counts and particle size distributions. However, the use of turbidity is insensitive to this approach in water treatment plant analysis since turbidity and particle counts are poorly correlated.

Filter modelling has evolved to relatively sophisticated levels using particle trajectory theory or adsorption theory. Pilot filtration studies or operating data are required to calibrate these models since none are able to predict performance when given only the physical and chemical characteristics of the influent particles and filter medium. Models can be a useful tool in predicting the changes in performance resulting from operational changes or raw water quality fluctuations once the models are calibrated by operational data. They should be seriously considered as an operating tool in existing plants.

Chemical pretreatment is important in preparing influent particles for removal in the filter. Only slow sand and precoat filters can normally operate efficiently without pretreatment. All other filters discussed in the review require pretreatment.

Rapid rate filter design procedures do not specifically consider effluent quality as a design parameter. Rather, headlosses are evaluated so filter run lengths can be ascertained. Headloss is a function of the porosity, friction, velocity, filter depth, medium size and shape. Optimization involves choosing a filter medium which produces the design

headlosses prior to or simultaneously with turbidity or particle breakthrough. Continuous effluent turbidity and filter headloss monitoring are the accepted means of control for rapid filters. Multi-media filters perform as well as rapid sand filters but have longer filter runs and operate under higher hydraulic loading rates. Declining rate filtration produces a superior effluent compared to constant rate filtration for operation of rapid rate filters.

Slow sand filters perform very well with little operating attention. Their design is generally based on prior experience. The formation of the "schmutzdecke" is very important in obtaining high quality effluent.

Both rapid and slow rate filters require periodic cleaning. In both cases, the performance of the cleaned filter is poor during a "ripening" period following start up. The methods for overcoming this problem include a "slow start" mode, filtering to waste, and the addition of chemicals to the wash water. Of these, filtering to waste appears the most reliable.

Alternate filtration technologies include variations of the rapid sand filter such as the use of different media, altered flow regimes, and continuous sand filters. Precoat filtration is another water filtration technology which received attention in the literature. Of the precoat filters, diatomaceous earth filters are the most common and perform well. However, their high cost tends to make them less attractive.

In conclusion, it appears that conventional, gravity, granular medium water filtration is capable of reliable, high

quality effluent (> 99% particle removal) provided that:

a. slow sand filters are used and are filtered to waste following cleaning; or

b. rapid rate filters are used with adequate pretreatment and start-up precautions such as filtering to waste; and

c. effluent turbidity is continuously monitored and the filter removed from service immediately after excessive turbidity has broken through (the literature suggests turbidity > 0.1 NTU is associated with rapid increases in particle counts); and

d. filter design is based on operational experience with the water to be treated using the proposed filter configuration.

2. INTRODUCTION

In March 1985, Alberta Environment, (Standards and Approvals Division, Municipal Engineering Branch) commissioned Underwood McLellan Ltd. to provide a report which reviewed available and pertinent literature on water filtration technologies.

2.1 BACKGROUND

Water filtration with disinfection is the minimum requirement for surface water treatment in the Province of Alberta. Filtration is also used in conjunction with other water treatment processes as part of the multiple barrier concept of producing safe drinking water.[1]

The importance of high quality water filtration cannot be overstated. Recent cases of giardiasis in Alberta have implicated inadequate surface water treatment as a possible reason for the outbreaks. Lack of filtration or reduced filtration efficiency as a result of questionable pretreatment may have been significant factors related to the outbreaks. Water filters are helpful in preventing other waterborne diseases which could be transmitted by microorganisms such as viruses and bacteria.[1,2] Most types of filters are not 100% effective in removing particles, including pathogenic microorganisms, however they are capable, given proper design and operation, of achieving removals of 99% or more.[3]

Increased emphasis on high quality filtration is illustrated by movement towards establishing a lower objective turbidity level for filtered waters. The current Guidlines for Canadian

Drinking Water Quality[4] specify an objective turbidity value of less than 1.0 NTU. Several researchers[1] including the American Water Works Association[5] have suggested that a 0.1 NTU standard is both desirable and achievable with conventional filtration technologies. Others suggest turbidity is an inadequate measure of the presence of microorganisms and have suggested the use of turbidity and particle counting methods.[6]

The subject of this report is to review common water filtration technologies and their ability to remove particles from water.

2.2 TERMS OF REFERENCE

The terms of reference for the report are as follows:

"Specifically the report is to review, summarize and comment upon the relevant technical literature on filter bed design and operation as it relates to both particle size and particle count removals. The general theory of filter design and predictive performance equation/models should be examined.

Common filter bed design characteristics such as:

a. type of filter media;
b. depth of filter media layer;
c. size and shape of different filter media;
d. filter media porosity; and
e. hydraulic loading rates and operating head

should be reviewed for each of the following types of filters:

a. rapid sand;
b. dual media;
c. slow sand;
d. multi-media.

The effect of different filter operating modes, such as constant rate, declining rate, filter to waste etc., on the performance of each of these types of filters should also be reviewed. The performance capabilities of different filter media and filter types should be reviewed and assessed in terms of turbidity and particle count and particle size removals. It is understood that the report will be written in a technical fashion with technical references cited within the text of the

report."

2.3 SCOPE OF REPORT

The terms of reference established by Alberta Environment were intended to restrict the literature review to readily available reference material (other promising references are listed in a bibliography at the end of the report). As a result, the report was done at the risk of omitting, or just touching on, some important aspects. For example:

- the report is confined to filtration of surface waters to produce potable water;
- the report emphasizes gravity filtration since pressure filters are more commonly used with groundwater or industrial filtration;
- filter design and operation aspects not related to particle removal are not reviewed. For example, headlosses and backwashing are not reviewed except in relation to their effect on particle removals;
- pretreatment processes are not covered other than to comment on how they influence particle removal; and
- only the filtration technologies listed in the terms of reference are reviewed in detail. However, some other filtration processes are briefly outlined in a separate section.

The remainder of this report is organized into several sections:

- fundamentals of particles, theory, and performance,
- slow sand filters,
- rapid sand filters,
- multi-media filters,
- other filter technologies; and
- conclusions.

2.4 TERMINOLOGY

The terminology of water filtration is based on traditional usage. Sand filtration is usually defined on the basis of hydraulic loading rate: either slow or rapid, constant or declining. The filters designed on this basis may or may not be backwashed as part of the design. Slow sand filters have traditionally not been backwashed whereas rapid sand and multi-media filters are normally backwashed.

This study will outline the general theory of filtration through porous media followed by a description of its application using various configurations. Multi-media filters have used a variety of media including sand, anthracite coal, activated carbon, garnet, flint, aluminum, glass, steel, polyurethane and polystyrene. Dual-media filters are considered a sub-classification of multi-media filters in this study. They normally consist of anthracite and sand.

Direct filtration refers to rapid rate filtration processes where the sedimentation and sometimes the flocculation unit processes are not used. The theory and operation of the filter is

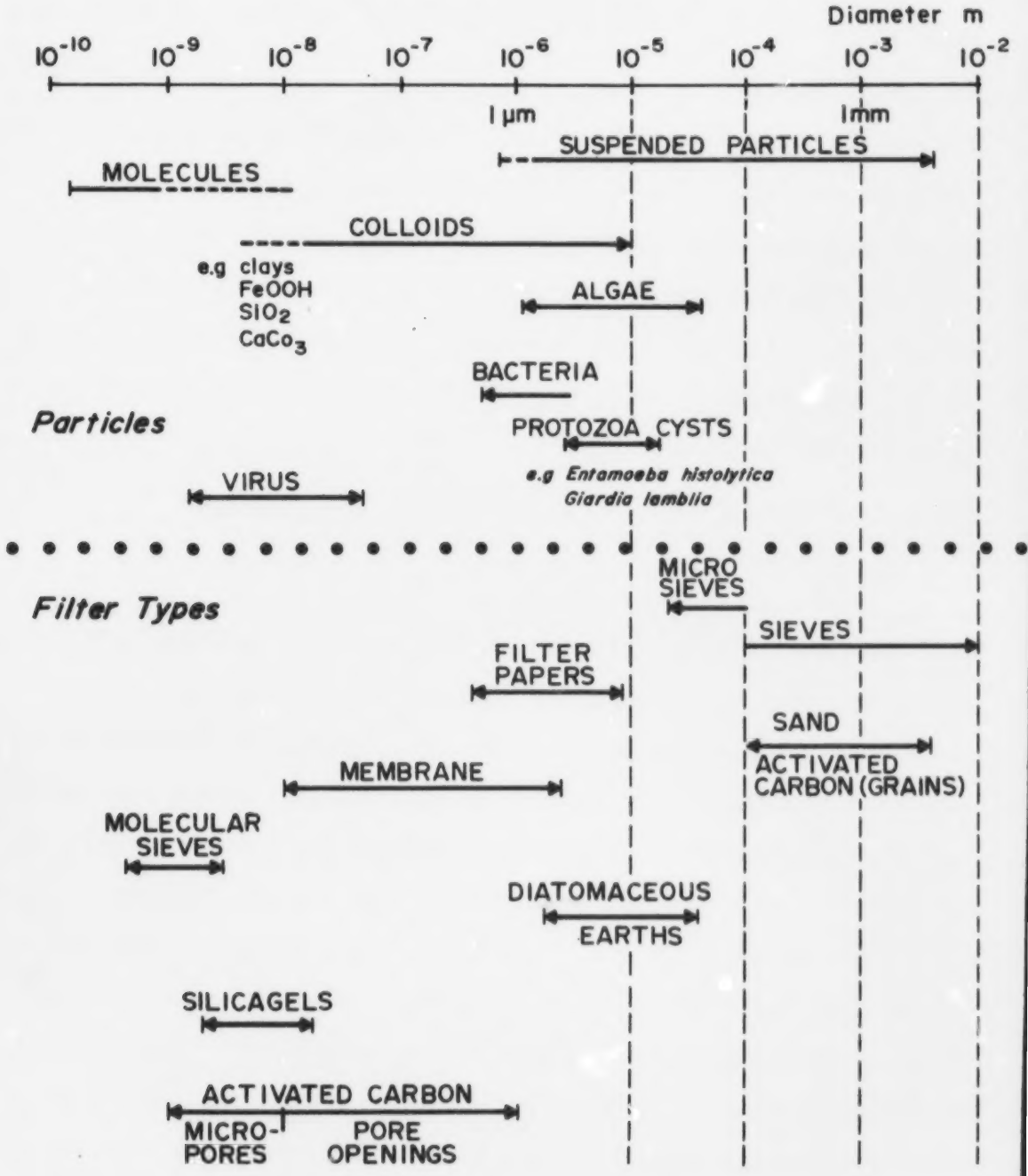
the same as in the other rapid rate filter processes.

3. FUNDAMENTAL CONSIDERATIONS

This section is intended to acquaint the reader with the fundamental aspects of filtration of potable water supplies. The types of particles found in surface waters and some of their properties are described before and after pretreatment. A review of performance criteria examines the advantages and disadvantages of various measures of performance. This is followed by a brief review of filtration theory including mathematical models and computer applications.

3.1 PARTICULATE MATTER IN WATER

Surface waters often contain a variety of shapes, sizes and types of particles. These can include organic macromolecules, inorganic precipitates, and biological solids. Pretreatment, most notably coagulation and softening, can produce other insoluble chemical products.[7] Figure 1 illustrates the relative sizes of some particles and common types of porous filter media.[8] Particles usually carry a negative surface charge in the neutral pH range.[8] This is significant in explaining the stability of some colloidal suspensions by the electric double layer theory discussed in detail elsewhere.[8] Other types of colloids are stable through chemical interactions with water. Coagulation is the destabilization of these dispersions by chemical means and flocculation refers to the transport step involving interparticle collisions which promote floc growth. Floc size and density are important characteristics in filtration and are controlled by the



SIZE RANGE OF PARTICLES FOUND IN NATURAL WATERS
(AFTER STUMM & MORGAN[6])

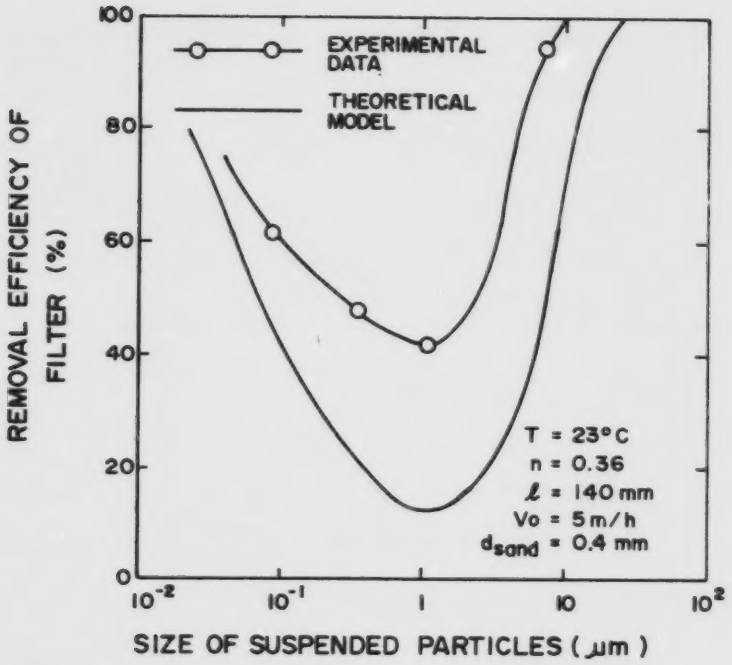
FIGURE 1

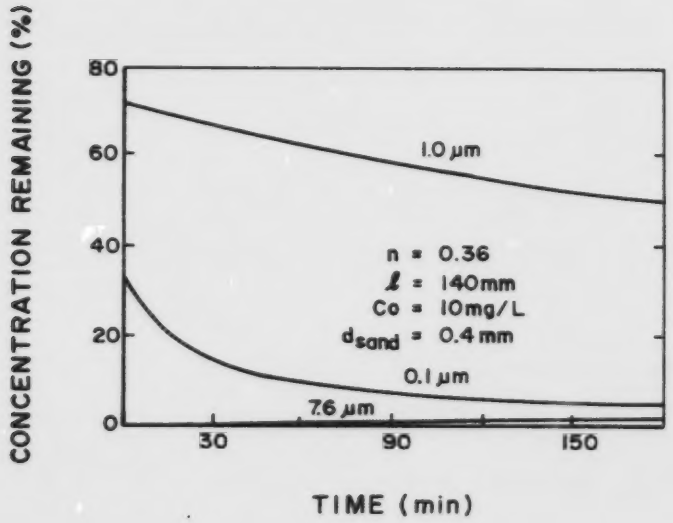
mean velocity gradient and contact time. Stumm and Morgan[9] provided a comprehensive review of the coagulation and flocculation of natural waters.

A knowledge of the chemical, physical, and biological properties of filter influent particles is important in understanding the interactions betweeen the water, particle, and filter medium.[9,10] O'Melia and Ali[11] and others[12,13] recognized this but determination of more than average particle size and concentration is difficult to perform routinely.

Particle size and concentration were found to influence filtration efficiency.[11,14] Figure 2 and Figure 3 illustrate the influence on effluent concentration by particle size and influent concentration respectively.[11] Kavanaugh et al[13] described the use of particle size distributions as an aid in designing filtration systems. They provided equations based on the power-law distribution function which allowed estimation of particle size distributions based on empirical data. This approach was limited to sizes of 1 μm or greater. Once the size fraction requiring removal was chosen, the appropriate process could be selected to remove the desired size fraction by equations given by Kavanaugh et al.[13]

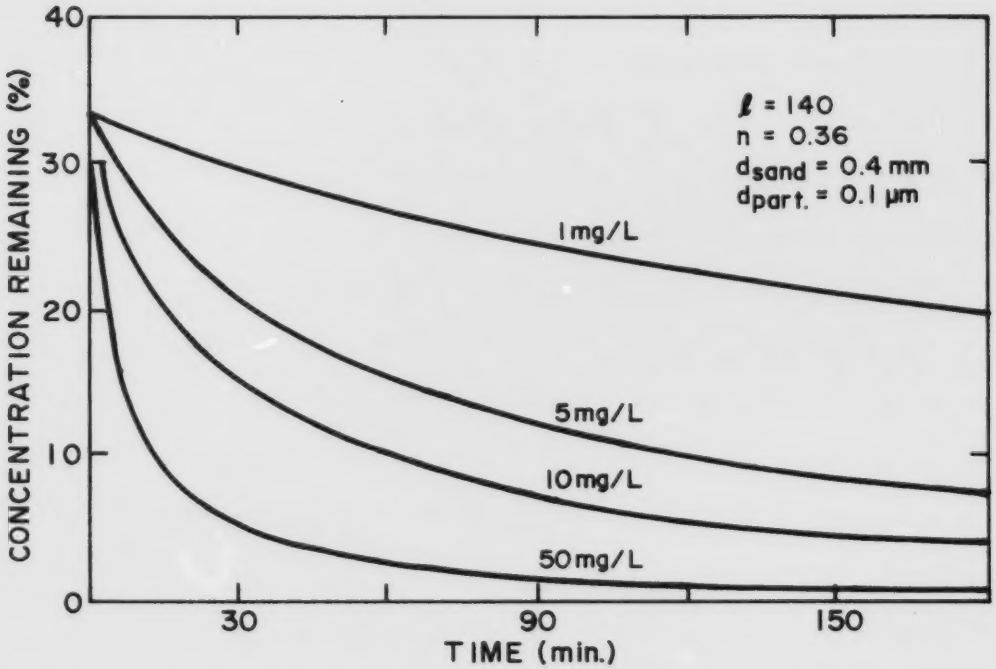
Freshwater[12] reviewed the methods for establishing the size of particles. He noted that although natural particles were rarely spherical, several methods were available for finding equivalent diameters. Unfortunately, the same particle could have several diameters depending on the method used. He also pointed out that an aggregated floc behaved differently than a discrete





EFFECTS OF PARTICLE SIZE ON FILTRATION
(AFTER O'MELIA & ALI[11] AND YAO ET AL[14])

FIGURE 2



EFFECTS OF INFLUENT CONCENTRATION ON FILTRATION
(AFTER O'MELIA & ALI[11])

FIGURE 3

particle and the floc should not be disturbed during measurement. O'Melia and Stumm[15] noted that the size and density of particles were important influences on the physical transport of solids in filters.

Treweek and Morgan[16] provided an excellent review of the methods for counting particles. Table 2 is from this source and compares the various techniques. Electron microscopy is capable of determining particles 0.001 to 100 μm in diameter.[12] The use of electronic devices such as the Coulter counter[17] is limited to the laboratory because of its expense and complexity.[16] Treweek and Morgan[18] described a model (see Table 2, spectrophotometric) which was able to predict turbidity from aggregate size distribution measurements. They were able to predict suspension turbidity to within 20% and able to study the shift in particle size distribution as a result of coagulation. This allowed a rational choice of filter medium grain size to remove the particles.

Pretreatment in the form of coagulation and flocculation and/or lime softening is commonly practised prior to filtration.[19] This prepares the remaining particulate matter for removal in the filter and reduces the mass loading on the filter by sedimentation prior to filtration. Conditioning of the influent water to maximize filtrability was not necessarily consistent with producing minimum influent turbidity.[20] Logsdon et al[21] suggested preconditioning and filtration should be considered as interdependent processes with the objective of eliminating particles from the filter effluent. Others[20,22,23]

Table 1 Experimental techniques for counting and sizing particles. (after Fretwell and Morgan[16])

Technique	Property Measured	Size Range (μm)	Description of Process	Disadvantages
Optical				
Microscope	Length/width	0.2-400	Visual observation and comparison of aggregates with calibrated slide or lens	Time consuming and laborious; judgement errors in estimating size
Microscope automated	Length/width	0.5 and up	Microscope slide or photograph electronically scanned to record aggregate images	Time consuming; expensive peripheral equipment
Light scattering (also laser scattering)	Light intensity	2-500	Intensity of light energy scattered from particle in direction of sensor	Varying refractive indices of heterogeneous particles; multiple scattering effects in aggregates; criticality of sensing angle
Light interruption	Light blockage	2-9000	Reduction of light intensity on sensor as aggregate passes by a dectector	Opacity of fluid medium; identical refractive indices of particle and fluid
Spectrophotometric	Light intensity	0.002 and up	Observation of reduction in light intensity upon passing through suspension of aggregates (turbidity)	Complicated relationship between turbidity and size, i.e., $T = \sum_i n_i \pi r_i^2 K_i$, where n_i = number of particles of radius, r_i, K_i = extinction coefficient which is function of relative refractive index, wavelength, and radius.
Visual	Length/width	20 and up	Observation of appearance and size of aggregates	Time consuming and laborious; judgement errors in establishing size
Sedimentation/filtration				
Gravity sedimentation	Velocity	0.1-100	Observation of steady-state aggregate velocity through suspending media	Density and shape factors of aggregate unknown; time-consuming and laborious
Centrifugal sedimentation	Velocity	0.02-10	Observation of steady-state aggregate velocity as centrifugal force drives aggregate through suspending media	Density and shape factors of aggregate unknown; shearing and distortion of aggregates
Membrane refiltration	Filterability	0.45 and up	Formation of filter cake on 0.45 μm filter by filtering suspension, followed by refiltration of filtrate through filter cake	Filtration time a function of both filter cake porosity and specific surface area of aggregates
Electronic				
Electrophoretic mobility	Velocity	0.1-100	Observation of steady-state aggregate velocity as potential difference draws aggregate through suspending media	Density and shape factor of aggregate unknown; velocity a function of both unbalanced charge density and aggregate diameter
Electrical resistance	Resistivity	0.5-900	Aggregate passes through aperture causing resistance change in electrolyte between two electrodes. Resulting voltage pulse is proportional to aggregate volume.	Blocking of aperture; expensive peripheral equipment

support the concept in terms of filtrability. Cleasby[22] demonstrated the difficulty of defining a universal filtrability index which could be used to indicate the probable efficiency of a filter.

Logarathan and Maier[24] investigated the surface chemistry of kaolinite and filter sand in terms of turbidity removal. Kaolinite surface properties were altered by pH changes and the addition of cations. They observed a near linear decrease in turbidity with pH as pH dropped below 7. Kaolinite apparently flocculated and formed larger particles. Others reported improvements in particle removal associated with coagulation.[23,24] Jorden[27] used electrophoretic (see Stumm and Morgan[4]) measurements to characterize the surface charge of influent particles and found improved filtration efficiency was related to increased negative surface charge. Others[28,29] reported contradictory results, finding that as the particle surface charge approached the isoelectric point (zero charge) peak removals occurred. Heertjes and Lerk[30] found the surface charge of filter sand grains changed from strongly negative to near zero as the filter run progressed. This suggested adsorption processes were operating at the sand grain surface.

The physical and chemical properties of particles are important to understand if their behaviour in the filter is to be predicted. Characterization of the particle size distribution and nature of the particle, be it organic, biological, or inorganic, is important as is a knowledge of the surface chemistry. The literature did not reveal the routine use of surface chemistry

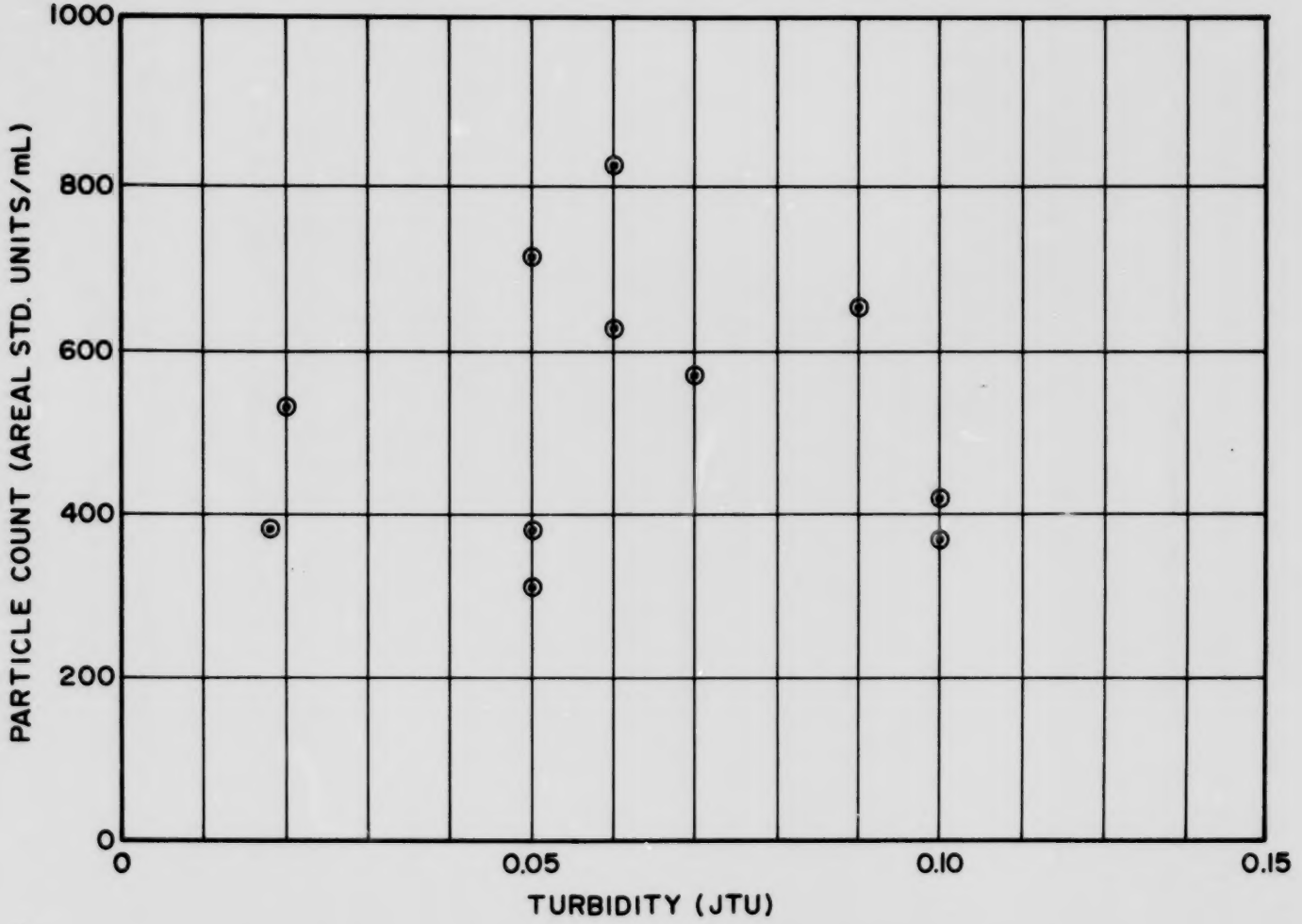
methods or particle characterization techniques in the treatment of potable water. Rather, dependence upon measures such as turbidity or non-filtrable residue (NFR) was common which may be inadequate in accurately assessing the number of particles and their behaviour during filtration.[4]

3.2 PERFORMANCE CRITERIA

Bishop[31] discussed the following parameters as measures of filter performance:

- turbidity of filter effluent;
- particle counting of the filter effluent;
- non-filtrable residue in the filter effluent;
- headloss in the filter; and
- net unit production of water.

In terms of particle removal efficiency, only the first three parameters are of value. Non-filtrable residue is of limited use in finished water since it is an insensitive measure of small particle sizes in dilute suspensions. Thus, turbidity and potentially particle counting, remain as the methods of evaluating finished water. Syrotynski[4] advocated the use of both turbidimetric and particle counting approaches in water with less than 5 TU. Turbidity measurements using nephelometric methods are considered the best and are capable of directly measuring 0.05 NTU.[32,33] Figures 4 and 5 are after Bishop.[31] The figures are a compilation of data obtained from a multi-media filter at various times and flow rates. As can be readily seen, there was little



TURBIDITY VERSUS PARTICLE COUNT JTU ≤ 0.10
(AFTER BISHOP[31])

FIGURE 4

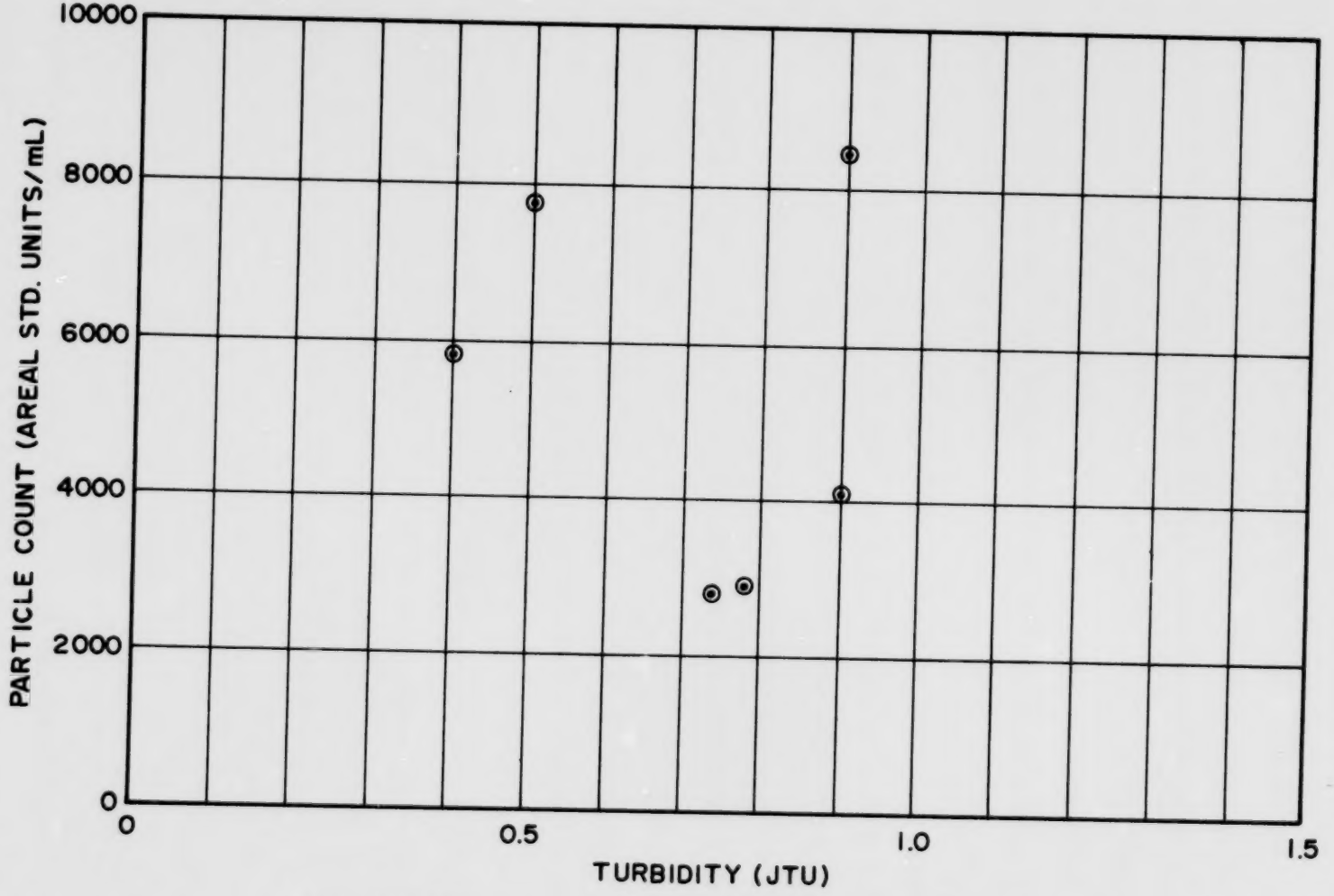


FIGURE 5

TURBIDITY VERSUS PARTICLE COUNT, JTU ≤ 1.0
(AFTER BISHOP[31])

relation between turbidity and particle counts for the individual ranges given. However, there was a marked reduction in particle counts when turbidity was less than 0.1 JTU compared to 1.0 JTU. Kukshtel et al[34] found little correlation between turbidity and particle counts at a desalination plant. Logsdon et al[35,36] supported this observation with their studies of Giardia lamblia cyst removals by filtration. They found that final turbidity levels less than 1.0 NTU did not ensure the absence of cysts. Also, minor increases in turbidity (0.05 to 0.10 NTU) were associated with much greater numbers of cysts in the filtrate. A goal of 0.1 NTU for finished waters could be set but the practicality of this was questioned given normal operating conditions in water filtration plants. Westerhoff[37] presented further data illustrating the lack of correlation between turbidity and particle counts. Therefore, the use of turbidity alone may not be an adequate or desirable criterion for monitoring filtration performance.[18] The approach of Treweek and Morgan[16,18] where particle counting and particle size distributions are used to evaluate the raw water characteristics should be considered further for routine application to water filtration.

3.3 REVIEW OF WATER FILTRATION THEORY

Ives[38] reviewed rapid filtration for the period prior to 1969. He characterized rapid and slow sand filters as being hydraulically similar but the biological activity associated with

the slow filter was significantly different from the action of a rapid filter where physical-chemical processes were predominant.

Ives outlined general concepts involved in water filtration. He cited three mechanisms: transport, attachment, and detachment. The transport mechanism considered the physical and hydrodynamic processes including straining, sedimentation and flocculation. The attachment mechanism involved particle electrical double layer interactions, van der Waals forces, hydration, and adsorption. Detachment mechanisms included scour due to increased interstitial velocity gradients in the bed or as a result of floc shearing. O'Melia and Stumm[38] also provided an excellent review of water filtration theory prior to 1967. Table 3 summarizes the removal mechanisms believed to be operating in a granular media filter bed.

Early water filter design was based on accumulated operating experience.[39,40,41] This resulted in conservative empirical designs based on hydraulic loading rate, headloss, and established filter media specifications. Empirical equations by Fair,[42] Stanley[39] and others[40,43] attempted to simplify filtration theory and describe it in terms of the physical properties of the filters such as sand grain size, porosity, approach velocity, and temperature. Their success was limited by the knowledge of filter processes at the time.

Concerns about predicting headloss and particle removal initiated the application of theoretical studies of flow through granular media to water filtration. Kozeny[44], Blake[45], Rose,[46] and Carman[47] investigated the hydraulics of packed granular

Table 3. Removal mechanisms in a granular filter. (after Metcalf and Eddy[118])

Mechanism	Description
1. Straining	
a. Mechanical	Particles larger than the pore space of the filtering medium are strained out mechanically
b. Chance contact	Particles smaller than the pore space are trapped within the filter by chance contact
2. Sedimentation	Particles settle on the filtering medium within the filter
3. Impaction	Heavy particles will not follow the flow streamlines
4. Interception	Many particles that move along in the streamline are removed when they come in contact with the surface of the filtering medium
5. Adhesion	Flocculant particles become attached to the surface of the filtering medium as they pass by. Because of the force of the flowing water, some material is sheared away before it becomes firmly attached and is pushed deeper into the filter bed. As the bed becomes clogged, the surface shear force increases to a point at which no additional material can be removed. Some material may break through the bottom of the filter, causing the sudden appearance of turbidity in the effluent
6. Chemical adsorption a. Bonding b. Chemical interaction 7. Physical adsorption a. Electrostatic forces b. Electokinetic forces c. van der Waals forces	Once a particle has been brought in contact with the surface of the filtering medium or with other particles, either one of these mechanisms, or both, may be responsible for holding it here
8. Flocculation	Large particles overtake smaller particles, join them, and form still larger particles. These particles are then removed by one or more of the above removal mechanisms
9. Biological growth	Biological growth within the filter will reduce the pore volume and may enhance the removal of particles with any of the above removal mechanisms (1 through 5)

filters producing equations still used today to predict headlosses during filtration (see Table 4). Deposition of particles in filter beds and subsequent clogging was studied by Eliassen[19,48] in an attempt to refine the theory of water flow through clean granular media. His work has not been widely accepted though it was important in introducing the problem of filter clogging.

Iwasaki[49] presented two equations which have been the basis for the physical particle removal models proposed by Ives[50,51] (see Table 5). These equations have inherent assumptions. The first one assumes that the effluent concentration is a function of the influent concentration such as in a first order chemical reaction. This has been justified by others.[52,53,54,55] The rate at which particle removal approaches 100% is a function of the filter coefficient which is a function of a number of diverse parameters as will be mentioned later. The second equation is the result of a mass balance around the filter bed. It assumes that the bed is a homogeneous, isotropic mass with a uniform media grain size, density, and porosity which remains constant with time. Also it assumes that the volume of solids accumulating in the filter equals that removed from the water. Because porosity is altered by deposits, the filter coefficient changes with time and location in the sand bed. Ives[56] suggested a correction for the filter coefficient which he inserted into his model. Others[50,55,57] have derived similar equations to Ives' for the filter coefficient. Ives solved his equation using numerical methods.[58] Constants can be evaluated by pilot studies. One

Table 4. Summary of clean bed headloss models. (after Metcalf and Eddy[118])

Equation	Definition of terms
Carman-Kozeny:[44,47]	C_d = coefficient of drag D = grain diameter, m f = friction factor g = gravity constant, 9.807 m/s^2 h = head loss, m K = Kozeny filtration constant, = 5 based on sieve openings, = 6 based on size of separation z = depth, m N_R = Reynolds number S = shape factor (varies between 6.0 and 7.7) v = filtration approach velocity, m/s n = porosity μ = viscosity, N.s/m^2 ν = kinematic viscosity, m^2/s ρ = density, kg/m^3 ψ = shape factor (usually 1)
$h = \frac{f}{\psi} \frac{(1-n)}{n^3} \frac{z}{D} \frac{v^2}{g}$	
$f = 150 \frac{(1-n)}{N_R} + 1.75$	
$N_R = \frac{Dv}{\nu}$	
Fair-Hatch:[84]	
$h = K\nu S^2 \frac{(1-n)^2}{n^3} \frac{z}{D^2} \frac{v}{g}$	
Rose:[46]	
$h = \frac{1.067}{\psi} C_d \frac{1}{n^4} \frac{z}{D} \frac{v^2}{g}$	
$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34$	

Table 5. Summary of relevant models describing performance

Equation	Definition of terms
Iwasaki:[49]	a,b,c = empirical exponents
$-\frac{\partial C}{\partial z} = \lambda C$	C = concentration
$-\frac{\partial C}{\partial z} = \frac{1}{v}\frac{\partial \sigma}{\partial t} + \frac{n-\sigma}{v}\frac{\partial C}{\partial t}$	C_o = initial concentration
Ives:[56]	D_p = influent particle diameter
$\frac{\lambda}{\lambda_o} = \left(1 + \frac{\beta\sigma}{n}\right)^a \left(1 - \frac{\sigma}{n}\right)^b \left(1 - \frac{\sigma}{\sigma_u}\right)^c$	D_s = sand grain diameter
O'Melia and coworkers:[11,14,15]	f(U) = Chi-square distribution function
$\eta_r = \alpha\,\eta + X\,\alpha_p\,\eta_p\left(\frac{D_p}{D_s}\right)^2$	i = hydraulic gradient
$\frac{\partial X}{\partial t} = \eta\,\alpha\,\varepsilon\,x_o v D_s^2 \frac{\pi}{4}$	K = Darcy's permeability coefficient
$\frac{\partial x}{\partial t} + v_o\frac{\partial x}{\partial z} + \frac{3}{2}\frac{(1-n)}{D_s} v\,x\,\eta_r = 0$	k_1 = accumulation coefficient
Adin and Rebhun:[71]	k_2 = detachment coefficient
$\frac{\partial \sigma}{\partial t} = k_1 v C (\sigma_u - \sigma) - k_2 \sigma i$	n = porosity
$\frac{\partial \sigma}{\partial V} = k_1 C (\sigma_u - \sigma) - k_2 \frac{\sigma}{K}$	P_c = cumulative probability = C/C_o
Hsiung and Cleasby:[68]	t = time
$f(U) = \frac{U^{\left(\frac{\upsilon}{2}-1\right)} e^{-\frac{U}{2}}}{2^{(\upsilon/2)}\,\Gamma(\upsilon/2)}$	V = volume of water
$P_c = \int f(U)\,dU$	v = filtration rate
	X = particles attached to sand
	x = particles remaining in solution
	x_o = initial particles in solution
	z = depth of filter bed
	α = attachment efficiency factor
	α_p = particle attachment efficiency factor
	β = geometric coefficient
	Γ = gamma function
	ε = fraction of attached particles acting as collectors
	η = single collector efficiency
	η_r = single collector removal efficiency
	η_p = contact efficiency of retained particle
	λ = filter coefficient
	λ_o = initial filter coefficient
	σ = specific deposit
	σ_u = ultimate specific deposit to clog filter
	υ = degree of freedom
	= sample time interval

limitation of his equation is that the filter coefficient is a function of the properties of the filter bed, pretreatment condition, filtration rate, and nature of influent particles. A change in any of these characteristics necessitates the reevaluation of the model parameters.[15] Ives and Sholji[59] examined the factors affecting the filter coefficient constants. They found filter efficiency measured in terms of the filter coefficient to be inversely proportional to hydraulic loading rate, the filter media grain size, porosity and the square of water viscosity. Their studies of uniform sand filters revealed that particle removal varied with bed depth as was to be expected by the first equation of Iwasaki (see Table 5). Fox and Cleasby[60] found Ives' model to be inadequate in describing the filtration of ferric hydroxide floc. O'Melia and Stumm[15] pointed out that no model could predict the effluent quality without extensive laboratory testing and that none were capable of predicting performance of the same filter for a different influent suspension. Ott and Bogan[61] supported this view based on their studies.

The importance of the chemical properties of the filter was recognized by several researchers[11,60,62] but few studies were directed specifically towards the chemical aspects. O'Melia and Stumm[15] proposed a two step model based on physical transport and chemical adsorption. They used the semi-empirical equation of Friedlander[52] to develop an equation describing the influent particle having the minimum contact frequency and the least likelihood of being removed. They developed a new expression for

the filter coefficient which predicted that influent particle size would significantly influence the filter coefficient. They applied the electric double layer model[8] to describe the interaction of particles and filter media. Mackrle and Mackrle[55] examined adhesion in sand filters in conjunction with filter hydrodynamics and formulated a model which predicted the reduction of solids with depth in any non-homogeneous filter media.

Yao et al[14] presented a further refinement of the two step model. They described filtration as analogous to coagulation and flocculation (see O'Melia, Table 5). Their model predicted particles of approximately 1.0 μm would be removed the least efficiently as shown in Figure 2. Others[28,29] had similar results. The results suggest diffusion is a significant mechanism in transporting particles less than 1.0 μm while settling and interception are significant for larger particle removal. Ison and Ives[43] examined a clean bed filter and found the filter coefficient to be an inverse function of hydraulic loading rate to the fourth power. This was the most significant parameter affecting the filter coefficient.

To this point, homogeneous granular beds have been considered except for Mackrle and Mackrle. Diaper and Ives[44,45] and Ives[46] have investigated size-graded media and stratified media. Diaper and Ives found the theory of filtration developed by Ives applied to this type of media.

Mohanka[47] extended the physical models of Ives and his coworkers to multilayer filtration. He solved the equations by

numerical methods. He found the filtration coefficient to be an inverse function of filtration rate and filter medium grain size.

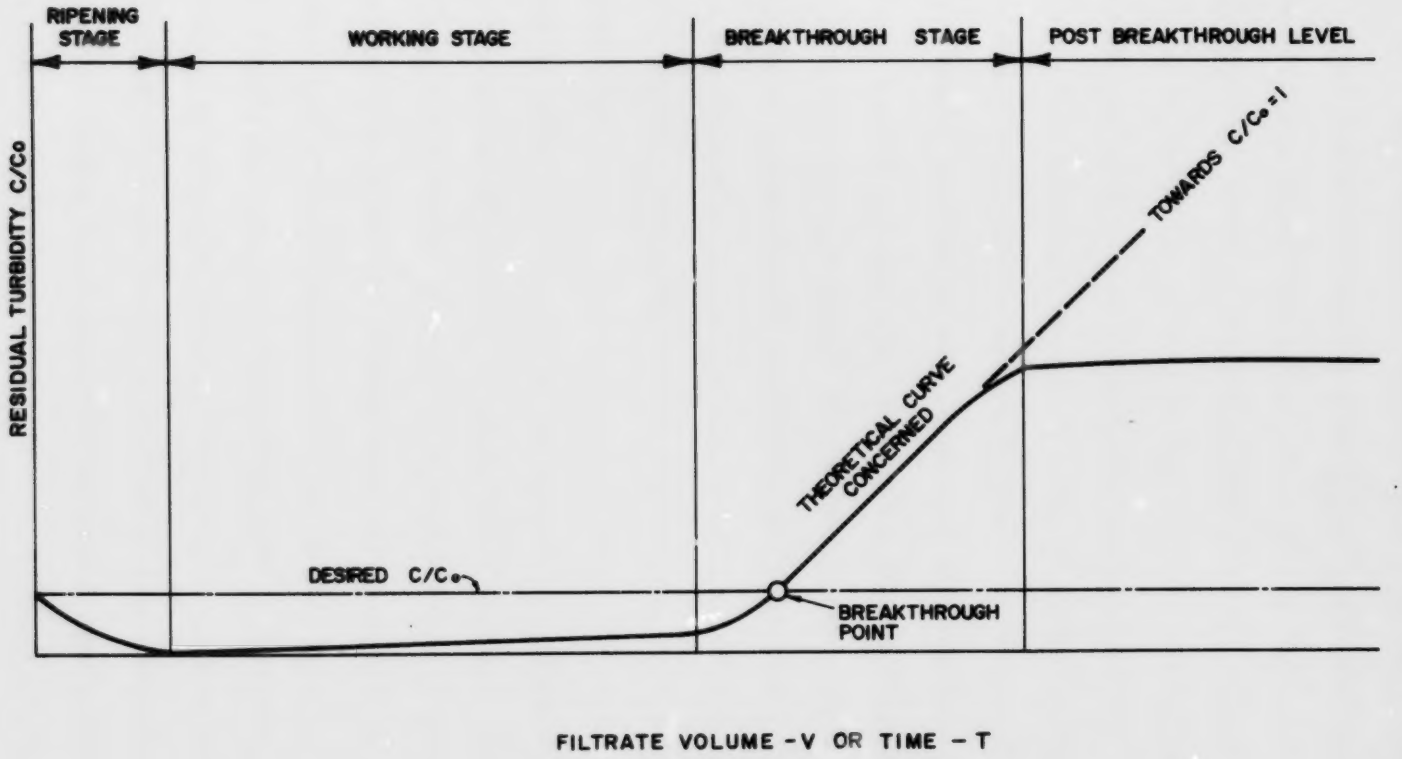
Hsiung and Cleasby[8] presented a statistical model (see Table 5) of filtration based on a chi-square probability distribution function. The model appeared to be quite good for their data and that of other researchers. They proposed a design approach based on their findings which provides the designer with flexibility in choosing flow rates and media size to achieve prescribed particle removals or headloss.

O'Melia and Ali[1] developed a model based on the earlier work of O'Melia and Stumm[5] and Yao et al.[4] Headlosses were based on an extension of the Carman-Kozeny equation.[4] The model considered the role of particles collected on the filter medium in removing other particles. A conclusion of note was that removal efficiency in a clean filter bed was independent of influent particle concentration. However, once the filter had ripened, performance was a function of influent particle concentration. The term ripening described the period of transition from a clean filter to one where retained particles enhanced the removal of other particles. O'Melia and Ali found removal efficiency increased with decreased grain size but found the effect of influent particle size and concentration was more significant. They noted that low turbidity water required deeper filters than high turbidity water since fewer particles collected on the sand grains when treating clean water. Ghosh et al[9] developed a model based on Iwasaki's[6] original equation but developed a new concept for the filter coefficient based on

trajectory equations for particles near a larger collector, such as is cypified by particles and sand grains. Spielman and Fitzpatrick[39] developed similar work. The model accounted for diffusion, hydrodynamic, gravitational, and interparticle forces. They found good agreement for the experimental conditions studied.

Adin and Rebhun[71] advanced a new concept of filtration based on granular activated carbon adsorption theory (see Table 5). The authors developed a differential equation describing the shape of the breakthrough curve shown in Figure 6. The model had terms describing the accumulation and detachment of solids. Four parameters determined from a simple bench scale test were required to calibrate the model. Statistical analysis of their model was not rigorous and further work is needed to determine its broader applicability. Adin[72] described the numerical method for solving the equation.

Willson et al[73] examined a problem identified by Ives[38]: the action of deep bed filters as flocculators. Using classic flocculation theory[8] and capillary hydraulics,[44] the authors found the formation of flocs to be controlled by the velocity gradient-time product, Gt. The value of G would control the size of floc particle in the filter bed and poor effluent quality was associated with increased Gt values which produced smaller floc sizes. This was consistent with other findings where influent particle size has been shown to be significant in filter efficiency.[38,39]



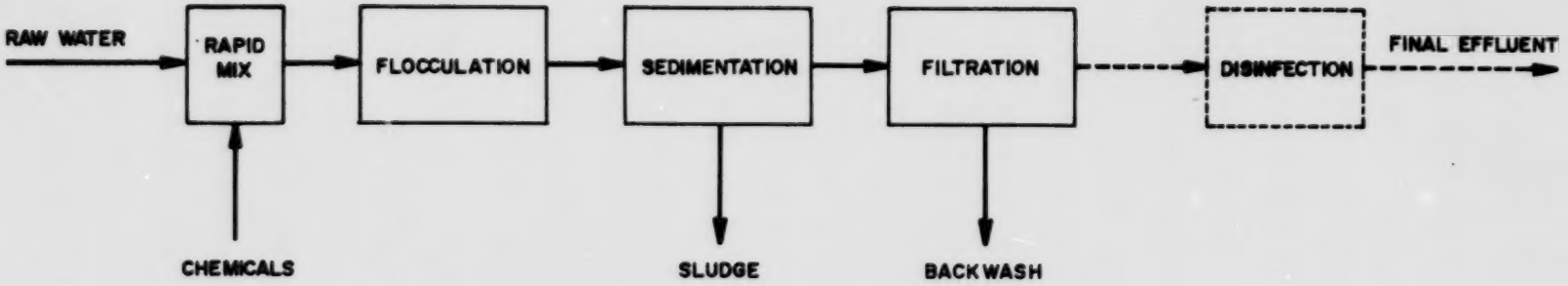
REPRESENTATION OF FILTRATION STAGES
(AFTER ADIN & REBHUN[71])

FIGURE 9

Toregas[14] studied particle attachment mechanisms. The study quantified the proportions of trapped particles which were removed by gravity or interparticle attachment. He concluded that 65% of the particles should be retained by the attachment mechanism for filtration to be effective.

Modelling of filters was discussed by Morley[15] and Cleasby.[16] Morley used Ives' early model which considered physical aspects only. Cleasby reviewed the mathematical models to 1975 and preferred the probability model of Hsiung and Cleasby[17] because of its wide applicability for predicting effluent performance. The literature did not reveal any other sources who advocated or opposed the use of Cleasby's approach. Tebbutt[18] observed that most models developed were restricted in their use to special conditions and laboratory studies were essential in optimizing performance. The use of rational experimental design and analysis to optimize the design of filters was briefly discussed.

A systems approach has received attention in recent years.[19,20] Figure 7 illustrates a typical water treatment process flow sheet for solids removal.[19] Lawler et al[21] developed a model for an integrated water treatment plant containing sub-models for flocculation, sedimentation, and filtration. Each process interacts with the other, affecting performance in predictable ways. Raw water characteristics were described by a particle size distribution of the turbidity causing particles. The model was useful for gaining insight into the theoretical phenomena involved in particle removal and their effect on



SCHEMATIC OF PARTICLE REMOVAL PROCESSES IN TYPICAL WATER TREATMENT PLANT
(AFTER RAMALEY ET AL[79])

FIGURE 7

overall plant performance. Ramaley et al[77] concluded that overall plant performance was sensitive to changes in flocculation velocity gradient, sedimentation residence time, and media size in the filters. Light suspensions (specific gravity definition) were more difficult to treat than heavy inorganic particle suspensions. Light suspensions required higher flocculation velocity gradients, longer sedimentation times, and smaller filter media to achieve acceptable performance.

The preceding discussion of theory and its evolution tends to remain in the realm of research and industrial chemical processes. The water treatment industry tends to use empirical approaches established 40 years ago as demonstrated by the design standards of some agencies.[80,81] The theoretical aspects of filtration tend to suggest a more current, rational approach is required in the design of water treatment filters if particle removal is a performance criterion. The use of pilot plant studies was advocated by several investigators to evaluate filtration design and performance for a given raw water supply, chemical pretreatment, and filter configuration.[77,82]

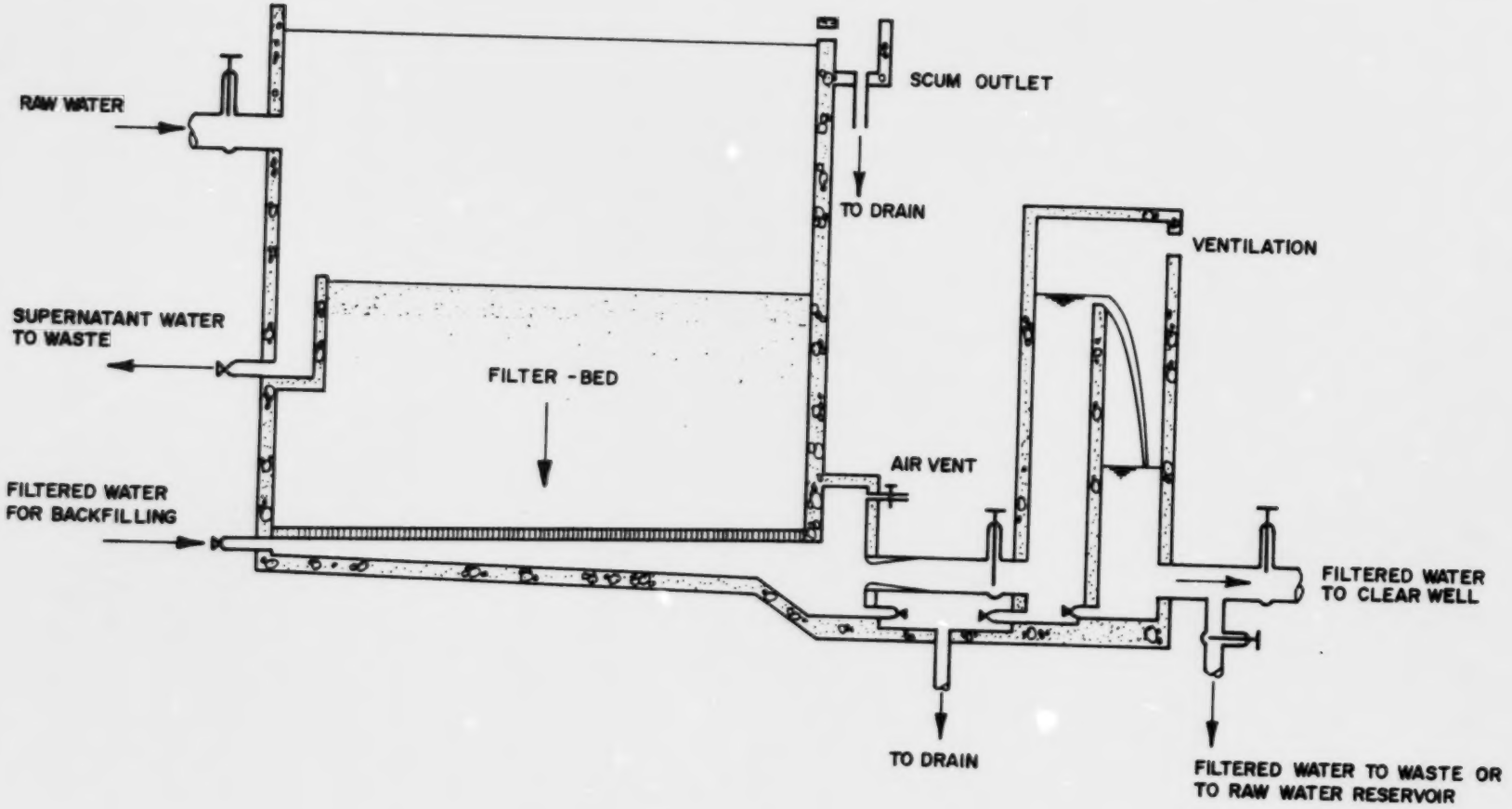
4. SLOW SAND FILTERS

4.1 DESCRIPTION

Slow sand filters are biologically active, ungraded sand filters which are designed to operate at hydraulic loading rates of 0.04 to 0.40 $m^3/(m^2.h)$.[43] Figure 8 illustrates the general layout of a slow sand filter and Figure 10(d) (see Section 5.1) represents the medium gradation. The mechanisms for particlate removal in a slow sand filter are the same as described in the previous section except the low hydraulic loading rate and the developed biological slime on the media greatly enhance the gravitational and adsorption processes which are effective in trapping and removing particles in the interstices of the filter medium.[43] One of the most significant features of a slow sand filter is the formation of a biologically diverse surface layer called the "schmutzdecke" during the filter ripening period. Physical straining and adsorption in the biological mass are significant in removing organic and inorganic particles alike.[43] Another important aspect is the long retention time relative to other filter types. This provides adequate time for diffusion, sedimentation, and adsorption to occur.[44]

4.2 DESIGN

The biological nature of the filter precludes the use of mathematical models in designing a slow sand filter. Rather,



SLOW SAND FILTER
(AFTER HUISMAN & WOOD[83])

FIGURE 8

years of experience have dictated the choice of media size, hydraulic loading rate, and headloss criteria for achieving an effluent of the desirable quality. Wagner and Lanoix[15] and Huisman and Wood[13] provided typical design criteria. Media gradation was defined by the effective grain size, D_{10}, and the coefficient of uniformity. The effective grain size is the seive size which allows 10% of the granular material to pass. The coefficient of uniformity is defined as the ratio of D_{60} to D_{10} where D_{60} is the seive size which passes 60% of the material. Wagner and Lanoix[15] suggested an effective grain size of 0.3 to 0.4 mm and coefficient of uniformity of 2.0 in a bed 1.0 m deep. Also, they stated that headlosses should not exceed 1.5 to 2.0 m before cleaning the filter and filtration rates should not exceed 0.1 m/h. Huisman and Wood[13] used a headloss equation (see Carman-Kozeny, Table 3) to estimate the effect of grain size and flow rate on headloss. The possibility of air binding (negative pressures) in the filter prompted them to suggest the use of a weir device to maintain a minimum water level above the filter (see Figure 8). Filtration rates could be raised to account for exceptional raw water quality. The empirical nature of the design of sand filters suggests pilot studies should be done to determine the operating characteristics of the filters prior to full scale design. This is supported by Fox et al[14] and others.[17]

4.3 OPERATING CONDITIONS

Filter run lengths are a function of the raw water quality and grain size.[3] Very little operating attention is required for slow sand filters. Flow rate, headloss, and effluent turbidity are the only daily checks required.[4] Flow rate may be adjusted to maintain a constant head on the filter to prevent overflow waste of raw water and to maintain a sufficient head on the filter. Once the headloss reaches the design limit, the filter is taken out of service and the top 50 to 75 mm are removed.[3] The filter is then placed back in service following a filter to waste period while the filter ripens. Experience has shown this to be necessary to maintain adequate effluent quality.[1] Attempts to gradually reinstate the filter without wasting were unsuccessful.[1] Cleaning is done using special mechanical scrapers in most North American installations.[3] Mechanical earthmoving equipment tends to compact the filter bed reducing the efficiency of the filter and its use should be avoided.[3] The recovered sand is cleaned and used to replace sand in filters after the bed depth is reduced to approximately 600 mm. This is necessary after twenty or thirty scrapings.[3]

4.4 PERFORMANCE

The performance of slow sand filters is affected by temperature, grain size, and hydraulic loading rates.[3] Cold climate regions may require enclosed filter beds to prevent freezing[3] or suitable allowances for ice accumulation above the

filter media.

Fox et al[4] reported better particle removal using filters with an effective grain size of 0.17 mm as opposed to one with 0.29 mm. They used constant flow rates. Another study[7] used sand with effective grain sizes of 0.51 and 0.44 mm and hydraulic loading rates of 0.1 to 0.4 m/h and found test particle (10 μm size) removals ranged from 98.5 to 99%. The slightly poorer removals were associated with the coarser sand and higher filtration rates. Huisman and Wood[13] reported that effluent quality was insensitive to filtration rate for the range tested (< 0.4 m/h). They concluded grain size was the most important consideration.

Wagner and Lanoix[5] reported bacteria removals ranged from 85 to 99% depending on the initial number. Fox et al[4] reported one to two log reductions (90 to 99% removal) of Giardia sized particles when using an effective grain size of 0.17 mm and a filtration rate of 0.12 m/h. Cleasby et al[6] had similar results using a slow sand filter with an effective grain size of 0.32 mm, a coefficient of uniformity of 1.44, and a filtration rate of 0.12 m/h. Hendricks et al[3] found Giardia removal to be affected by the maturity of the biological slime. Temperature, effective sand size (< 0.28 mm), sand bed depth (> 0.50 m), and filtration rate (< 0.40 m/h) did not affect the removals of Giardia. They also suggested pretreatment by coagulation, flocculation, and sedimentation was important for consistently high removals of the protozoa. Kuntschik[9] used a gravel layer to pretreat raw water which extended his filter runs. Others[8] studied slow sand

filtration removal of reovirus and Escherichia coli using effective grain sizes of 0.11 to 0.28 mm, coefficients of uniformity of 2.1 to 7.7, and a hydraulic loading rate of 0.2 m/h. They concluded sand grain size had no significant effect on removal efficiencies.

Slezak et al'' compiled some data on slow sand filtration in the United States. Their data summarized media characteristics and cost, filtration rates, and filter run lengths for a number of facilities. Effective grain size ranged from 0.12 to 1.4 mm, coefficient of uniformity ranged from 1.2 to 3.5, and cost of sand ranged from $4.35 to $63.00 (US) per tonne. Longest filter run lengths were during the winter season.

The data on the performance of slow sand filters is occasionally contradictory when speaking of particles in general. However, looking at a specific size distribution including the characteristic size of some protozoa, there appears to be a correlation between grain size and removal efficiency. None of the reviewed studies used satisfactory experimental design or statistical analysis to clarify the correlation. This area requires further work.

5. RAPID SAND FILTERS

5.1 DESCRIPTION

Rapid sand filters are granular media filters operated at rates greater than 5 $m^3/(m^2.h)$.[92] Normally these filters use sand as the filter medium but several alternate media have been tested.[67,93,94] Figure 9 illustrates a typical arrangement of a rapid, granular media filter which utilizes hydraulic backwashing to clean the filter. Media types other than sand are discussed in Section 6.

Rapid sand filters effectively treat dilute suspensions (< 500 mg/L) of particles which range in size from 0.1 to 50 μm.[38] Pretreatment by coagulation, flocculation and/or sedimentation has been recommended for other sizes of particles and considered essential regardless of particle size by some investigators.[2,92]

Figure 10(a) demonstrates an inherent problem with monomedia rapid sand filters: backwashing results in a size-graded medium which leaves the finest particles at the surface. Figure 10(b) is a more desirable configuration which is not possible to achieve using a hydraulically placed single medium.[20] This problem led to the use of sand with a uniformity coefficient of less than 1.5 which improved the depth of particle penetration, reduced the rate of headloss, and contributed to longer filter runs.[84]

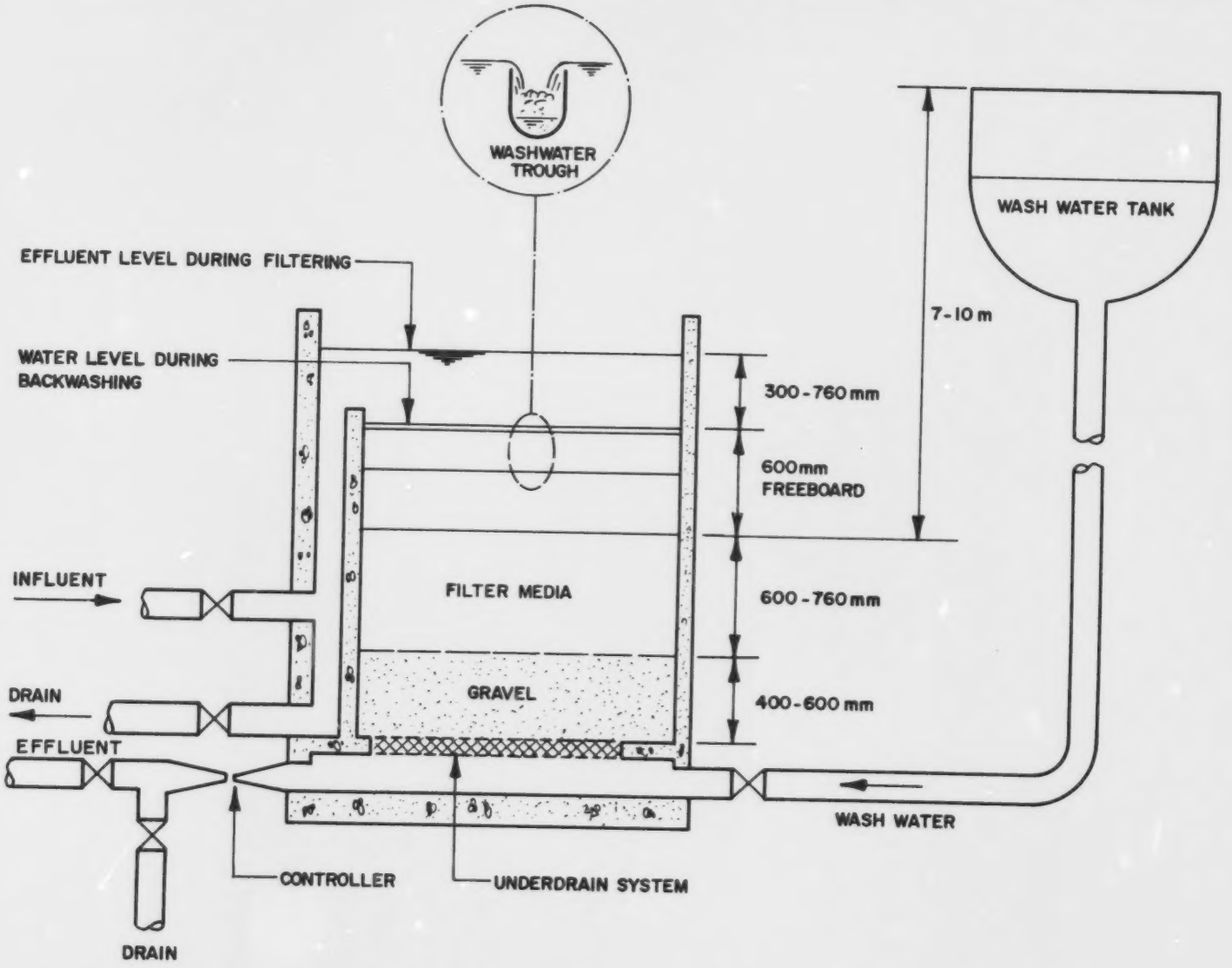
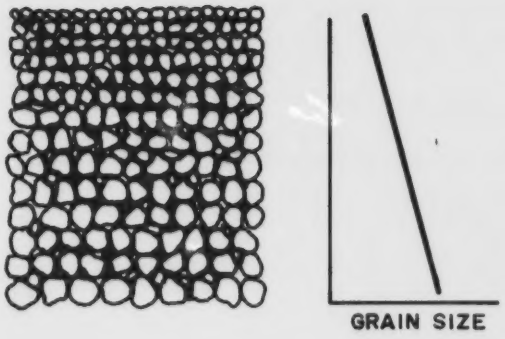
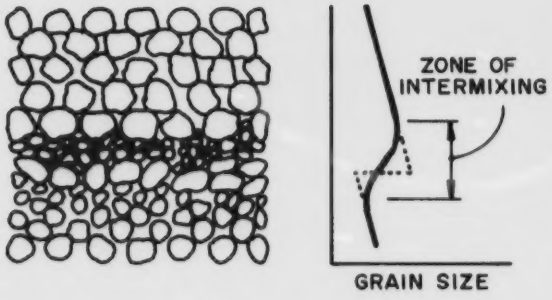


FIGURE 9

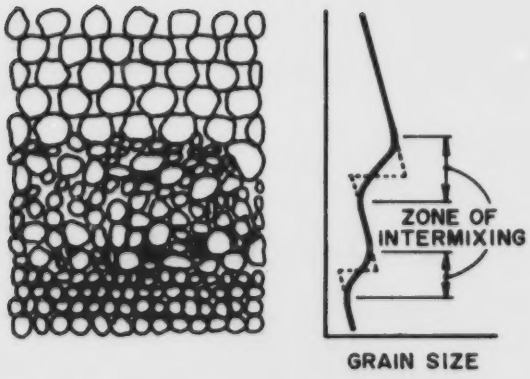
TYPICAL DOWNFLOW, GRANULAR - MEDIUM, GRAVITY - FLOW FILTER WITH BACKWASHING PROVISION
(AFTER METCALF & EDDY[118])



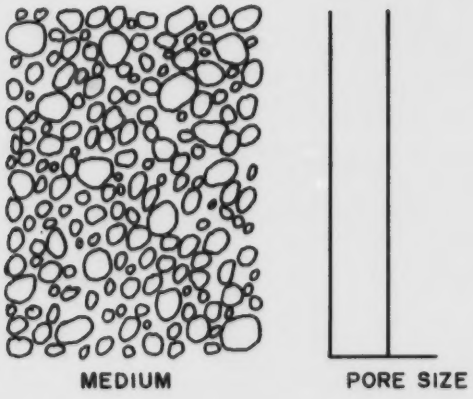
(a) CROSS SECTION THROUGH SINGLE-MEDIUM BED



(b) CROSS SECTION THROUGH DUAL-MEDIUM BED



(c) CROSS SECTION THROUGH TRI-MEDIUM BED



(d) CROSS SECTION THROUGH SINGLE MEDIUM UNSTRATIFIED FILTER BED

ARRANGEMENTS OF FILTER MEDIA
(AFTER METCALF & EDDY[118])

FIGURE 10

5.2 DESIGN

The design of rapid sand filters is based on media characteristics, headloss, and maximum filtration rates guided by the regulations of approval agencies.[8,9,11,15] The Ten State Standards[11] require the designer to justify the hydraulic loading rate. They also specify the filter media characteristics. Overall performance of the filter in meeting water quality criteria is the responsibility of the designer. Table 1 summarizes common rapid sand filtration design parameters which are representative of those reported in the literature.

It becomes apparent the designer needs only some basic information to design rapid sand filters such as:[6,7,9]

- hydraulic loading rate;
- headloss;
- effective grain size of the sand;
- uniformity coefficient;
- initial turbidity;
- filter bed depth;
- pretreatment;
- desired effluent turbidity; and
- previous experience with a similar water supply.

While the theory of water filtration can be described by mathematical models as discussed earlier, the routine application of theory for rapid filter design apparently is not documented in the literature. Ives[9] described the use of pilot filters to obtain data on filter performance as a function of headloss and turbidity removal which could be used for design. Letterman[10]

stated that pilot plant studies were required for all non-conventional applications since models were not advanced enough to accurately predict filter performance (using particle criterion) given the normal design criteria.

Cleasby and Baumann[10] concluded rapid sand filters pass particles even at low filtration rates (< 5 m/h), therefore, standard rates do not ensure consistent quality from plant to plant. Significantly higher rates can be used at some plants without degeneration of effluent quality.

Hudson[18] and Cleasby[22] attempted to overcome the difficulties of design models by the use of a filtrability index. Cleasby's was based on pilot studies to evaluate the filter coefficient and specific deposits which, when combined with headloss, could indicate the relative filtrability of a raw water. Neither one has found application on a routine basis.

The use of pilot studies and the design of full scale plants depends upon scale-up. Relatively little information was found regarding scale-up of rapid sand filtration facilities. Ives and Davis[21,102] discussed scale-up in terms of models and pilot performance. No scaling factors were found.

The design of rapid sand filters in the 1980's appears to be based on standards and experience developed over the past 50 to 60 years. The poor correlation between turbidity and particle counts suggests filter design experience for turbidity removal is inadequate when pathogenic organisms such as protozoal cysts may be present in the raw water supply. The review found pilot studies of particle removal were generally useful prior to the

design and construction of a full scale facility.

5.3 OPERATING CONDITIONS

There are two conditions which can influence particle removal under normal operating conditions: flow control and filter cleaning.

Cleasby[103] reviewed the common means of filter rate control in rapid sand filtration. The traditional method is by constant rate filtration where the effluent flow rate is controlled by a valve. A variation of this is constant water level control where the effluent is controlled to maintain constant water levels. These approaches to hydraulic loading control have several disadvantages the major one being that rapid changes (surges) in filtration rate cause poor quality effluent.[104] Influent flow splitting was another option discussed by Cleasby. If plant influent flow rates remain constant, each filter can operate under constant rate conditions by means of an influent weir box. If a filter is removed for cleaning, the other filters gradually increase their flow rates in compensation. Declining or variable rate flow control has been lauded by several authors as superior to the ones described above.[7,96,104] This operating mode was discussed by Cleasby and Di Bernardo[105] in detail. Declining rate filters operate by means of a common influent header pipe. As a filter becomes clogged the flow is transferred to a cleaner filter maintaining nearly equal water levels in each filter with levels rising and falling as a function of system headloss and

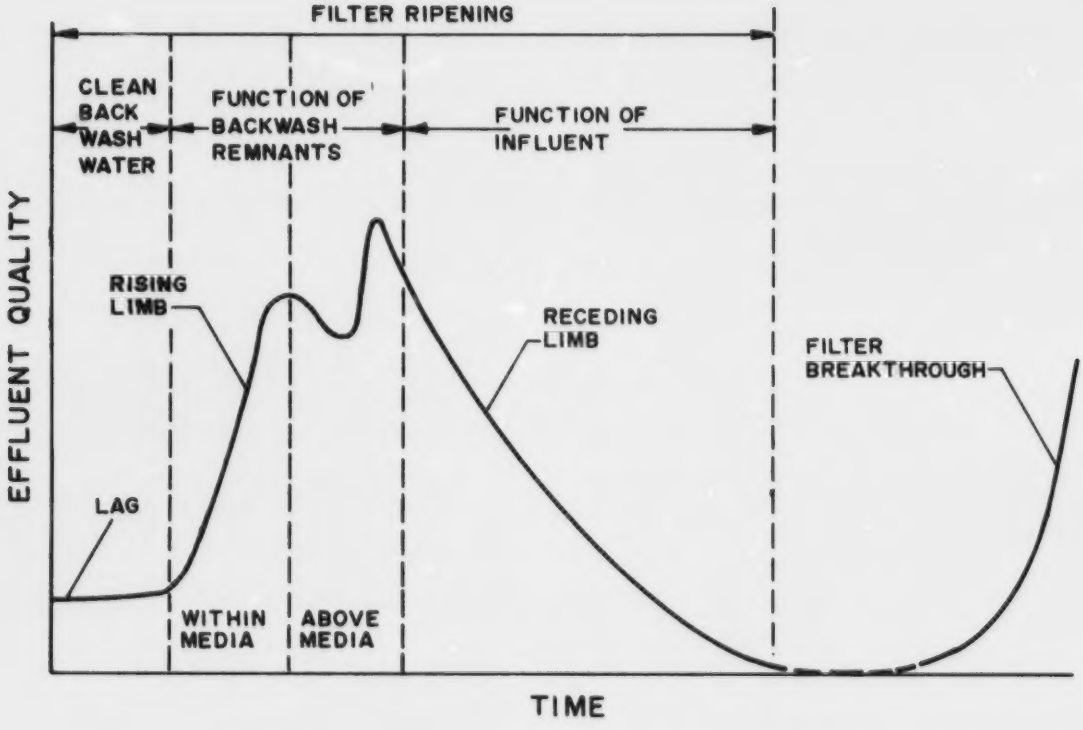
the number of filters in service. This causes a filter to operate with a steadily decreasing filtration rate over the filter run. These gradual changes in rate account for the high quality effluent particularly near the end of a run.[99,100] A comparison of declining rate and constant rate filtration is given in Table 6. Other investigators found declining rate flow control produced superior effluent quality in addition to longer filter runs.[94,97]

Cornwell et al[98] pointed out that many regulatory agencies did not understand the principles of declining rate filtration and were reluctant to endorse them. Cleasby and his coworkers[98,99] suggested the use of declining rate filtration as a simple modification which could improve the performance of rapid sand filters.

Backwashing of filters occurs when: (a) design headlosses are reached; or (b) when breakthrough occurs.[99] Johnson and Cleasby[10] provided a detailed account of the effect backwashing has on effluent quality. Their survey of earlier work revealed a consensus that clean sand filters provide a better quality effluent. Their study revealed that there is an optimum backwash rate and duration which would produce the best filter effluent. Also, filter bed expansion during backwash has an optimum level. They concluded from their study that 43 $m^3/(m^2.h)$ for 6 to 12 minutes and a bed expansion of 16 to 18% is optimum. Another study[11] analytically examined the problem of filter backwashing and the subsequent poor effluent quality during start-up (see Figure 11). The lag period was associated with the relatively

Table 6. Comparison of declining rate and constant rate filtration. (after Bryant[96])

Characteristics	Declining Rate	Constant Rate
Piping Size	Individual filter piping sized to result in proper headloss at maximum expected starting rate.	Individual filter and header piping sized for maximum economy at reasonable headlosses.
Filter Surface Area	Usually the same as for constant rate. The average filter rate during run should be comparable to constant rate.	Determined by maximum rate allowed or by test demonstrations to be reliably effective.
Depth of Filter Box	Sum of depth of filter underdrain and support media losses; maximum headloss expected through media and freeboard.	Same as for variable rate.
Loss of Head	Usually 0.6 or 1.0 m between top of media and clearwell during early plant life and 2.1 to 2.7 m at design flow.	Usually 2.1 to 2.7 m throughout plant life.
Length of Filter Run	30 to 40% longer runs than constant rate, which produces about 20% more water.	
Breakthrough at End of Runs	Lower filter rates at end of runs results in lower shearing forces which reduces chance of breakthrough.	Shearing forces remain constant.
Operation and Water Quality During Changes in Plant Production	Operator adjusts pumpage and filters gradually adjust themselves. No momentary breakthrough during increases.	Operator adjusts pumps and either changes number of filters in service or changes master rate controller setting. Sudden increases in filtration rate will likely cause breakthrough.
Operation During Raw Water Quality Changes	Operator changes length of filter run.	Operator changes length of filter run.
Operation During Temporary Outage of Wash Water System	All filters will automatically approach constant rate operation as backwashes are skipped.	Operator puts more filters in operation as dirty filter becomes plugged.
Increasing Plant Capacity	Ream or replace orifice plates.	Install larger rate controllers.



CHARACTERISTICS OF INITIAL EFFLUENT QUALITY
(AFTER AMIRTHARAJAH & WETSTEIN[111])

FIGURE 11

clean water in the filter galleries and the two peaks were associated with backwash remnants in the media and on the filter bed surface. The long recessional limb was postulated to be an interfacial effect between backwash remnants and influent water. The authors and others[2,11,13] suggested filtering to waste as a method of preventing backwash products from contaminating the treated water. As an alternative to this, Hudson[7] and others[11] considered a "slow start" method of avoiding filtering to waste. Hudson reported that a maximum rate of hydraulic loading increase was 3% per minute. This method was unsuccessful in slow sand filtration.[7] Little experience with this method was reported in the literature. Harris[11,13] used nonionic polyelectrolytes in the washwater to immediately improve effluent quality following backwashing. Qureshi[11,12] confirmed the findings of Amirtharajah and Wetstein.[11] He thought that extended backwash times and higher rates may mitigate the problem. It was thought the intensity of the poor quality period may be heightened by the use of declining rate filtration which is characterized by maximum filtration rates immediately after backwashing.

In summary, there were few reports on the impact of backwashing on effluent quality but the reviewed studies indicated that filtering to waste appears to be the most promising method to ensure the removal of excessive particulate matter from the finished water following backwashing. Alternatives are not numerous or well documented, but include polyelectrolyte addition to wash water and the use of a "slow start" mode.

5.4 PERFORMANCE

The performance of rapid sand filters for particulate removal ranged from poor to excellent.[3,4] Logsdon et al[3,4] studied the performance of pilot rapid sand filters in removing Giardia cysts and cyst models. Filtration rates were 10 m/h and removals ranged from 59.2 to 99.98%. These removals were based on pretreatment involving coagulation and sedimentation. Test runs with no pretreatment had removals of 59 to 94%. They concluded that a properly operated filter with pretreated water (coagulation) would reduce the number of cyst sized particles to a low level but not entirely eliminate their presence in the filter effluent. Al-Ani and Hendricks[1,4] also studied rapid sand filtration for the removal of Giardia cysts. Their pilot filter was operated at 5.2 and 13 m/h and contained sand with effective size of 0.45 mm and coefficient of uniformity of 1.5. Without coagulation pretreatment, removals ranged from 75 to 92%. However, when alum was used alone or in combination with polyelectrolytes, removals were greater than 99% in 10 of 13 runs for alum and 14 of 16 runs for those with alum and polyelectrolyte.

Several studies[23,115,116,117] evaluated the use of filter aids for enhancing the performance of rapid sand filters. Generally, filter aids improved removals of particles.

Operational problems of rapid filters and suggested solutions are summarized in Table 7. These problems can unpredictably affect the performance of a filter.

Table 7. Summary of common problems in the filtration of water. (after Metcalf and Eddy[118])

Problem	Description
Turbidity breakthrough	Unacceptable levels of turbidity are recorded in the effluent from the filter, even though the terminal head loss has not been reached. To control the buildup of effluent turbidity levels, chemicals and polymers have been added ahead of the filter bed, and polymers have been added within the filter bed. The point of chemical or polymer addition must be determined locally.
Mudball formation	Mudballs are agglomerations of floc, dirt, and the filtering media. If the mudballs are not removed, they will grow into large masses that often sink into the filter bed and ultimately reduce the effectiveness of the filtering and backwashing operations. The formation of mudballs can be controlled by auxiliary washing processes, such as air scour or water surface wash concurrent with, or followed by, water wash alone.
Development of cracks and contraction of filter bed	If the filter bed is not cleaned properly, the grains of the filtering medium become coated. As the filter compresses, cracks develop, especially at the sidewalls of the filter. Ultimately, mudballs may develop. This problem can be controlled by adequate backwashing and scouring.
Loss of filtering medium or media (mechanical)	In time, some of the filtering medium or media may be lost during backwashing and through the underdrain system (where the gravel support has been upset or the underdrain system has been installed improperly). The mechanical loss of the filtering medium can be minimized through the proper placement of the wash-water troughs and underdrain system. Special baffles for use with wash-water troughs have also proved to be effective.
Loss of filtering medium or media (optional)	Depending on the characteristics of the influent particles, grains of the filtering medium can become attached to it, forming aggregates light enough to be floated away during the backwashing operations. This problem can be minimized by the addition of an auxiliary air and/or water scouring system.
Gravel mounding	Gravel mounding occurs when the various layers of the support gravel are disrupted by the application of excessive rates of flow during the backwashing operation. A gravel support with an additional 50 to 74 mm layer of high-density material, such as ilmenite or garnet, can be used to overcome this problem. Gravel mounding is not a problem in uniformly graded filters.

Hudson'' reported that the use of pilot plants in parallel with a full size plant was useful in monitoring the performance of the plant. Also it allowed the operators to be aware of imminent changes in performance due to raw water quality variations by operating the pilot filters at a slightly higher filtration rate than their full scale counterparts. This allowed time for corrective measures to be taken within the full scale plant.

6. MULTI-MEDIA FILTERS

6.1 DESCRIPTION

Multi-media filters are a special type of rapid sand filter which has two or more types of filter medium.[1,3] The use of media with different sizes and densities promotes reverse grading of the media following backwashing as shown in Figure 10(b) and (c). This results in better penetration of particles into the filter.[1,3] Figure 10(a) is the result of backwashing monomedium rapid filters which shows how only the upper, fine part is effective in particle removal. Common types of multi-media filters include:[4,11,13,18]

- dual-media, consisting of anthracite coal and sand;
- tri-media, comprised of anthracite coal, sand, and commonly garnet; and
- exotic multi-layer designs which may be a combination of plastic beads, anthracite coal, sand, garnet, activated carbon, or magnetite.

The general filter configuration is similar to that of Figure 9. Multi-media filters have become popular because they permit the use of higher filtration rates and longer filter runs which lead to a more economical filtration operation.[11,13]

6.2 DESIGN

Much of the discussion regarding the design of rapid sand filters is applicable here. The most significant feature is the higher filtration rate of multi-media filters.[4] Table 8 summarizes media characteristics and hydraulic loading rates for multi-media filtration.

Thanh et al[122] optimized the amounts of anthracite and sand in a dual-media filter using Mohanka's[7] modelling approach and an optimization technique. They demonstrated the rule of thumb, 2:1 anthracite-sand depth ratio, was not necessarily the best. Depending on filter bed depth and filtration rate, the optimum ratio varied from 0.9 to 4.8. Conley and Hsiung[123] described another method of selecting the proportions of media for a multi-media filter based on an empirical approach. The first iteration involved proportioning based on media size. After testing performance, the proportions were adjusted if necessary. They also presented a method for choosing the size ratios of each layer based on characteristics of media in adjacent layers. Vigneswaran and Mazumdar[124] examined the selection of anthracite-sand size ratios using effluent quality or headloss as the criterion. Table 9 summarizes methods of calculating size ratios.[84,122,124]

These methods for determining the depth of each medium do not appear to be used in practice. The regulatory agencies tend to specify depths from past experience.[89]

Table 8. Typical design data for multi-media filters. (after Metcalf & Eddy[118])

Characteristic	Value	
	Range	Typical
Dual-medium:		
Anthracite:		
Depth, mm	300-600	450
Effective size, mm	0.8-2.0	1.2
Uniformity coefficient	1.3-1.8	1.6
Sand:		
Depth, mm	150-300	300
Effective size, mm	0.4-0.8	0.55
Uniformity coefficient	1.2-1.6	1.5
Filtration rate, m/h	4.8-24	12
Multi-medium:		
Anthracite (top layer of quadmedium filter):		
Depth, mm	200-400	200
Effective size, mm	1.3-2.0	1.6
Uniformity coefficient	1.5-1.8	1.6
Anthracite (second layer of quadmedium filter):		
Depth, mm	100-400	200
Effective size, mm	1.0-1.6	1.2
Uniformity coefficient	1.5-1.8	1.6
Anthracite (top layer of tri-medium filter):		
Depth, mm	200-500	400
Effective size, mm	1.0-2.0	1.4
Uniformity coefficient	1.4-1.8	1.6
Sand:		
Depth, mm	200-400	250
Effective size, mm	0.4-0.8	0.5
Uniformity coefficient	1.3-1.8	1.6
Garnet or ilmenite:		
Depth, mm	50-150	100
Effective size, mm	0.2-0.6	0.3
Uniformity coefficient	1.5-1.8	1.6
Filtration rate, m/h	4.8-24	12

Table 9. Calculated size ratios to cause intermixing of filter media. (after Vigneswaran & Mazumdar[124])

Researcher	Equations Used	Calculated Size Ratio	Comments
Fair et al.[84]	$\frac{D_a}{D_s} = \frac{\psi_s}{\psi_a}\left[\frac{\rho_s - \rho}{\rho_a - \rho}\right]^{1/2}$	2.38:1	Neglects settling, based on laminar flow backwash
Conley[125]	$\frac{D_a}{D_s} = \frac{1}{1.6}\left[\frac{\rho_s - \rho_m}{\rho_a - \rho_m}\right]$	2.63:1	Neglects backwashing, considers hindered settling
McCabe & Smith[126]	$\frac{D_a}{D_s} = \frac{\psi_s}{\psi_a}\left[\frac{\rho_s - \rho_m}{\rho_a - \rho_m}\right]^{1/2}$	2.73:1	Neglects backwashing, considers hindered settling

Where: D_a and D_s are the diameters of anthracite and sand grains, m

ψ_a and ψ_s are the shape factors of anthracite and sand

ρ, ρ_a, ρ_m, ρ_s are the densities of suspension, anthracite, mixed media and sand respectively, kg/m^3

6.3 OPERATING CONDITIONS

Again, the discussion of operating conditions for rapid sand filters is similar to that for multi-media filters. The significant difference between the two types of filter occurs in the backwashing mode.

There has been some discussion in the literature regarding the intermixing of media in multi-media filters.[125,127,128] Vigneswaran and Mazumdar[124] formulated an equation to predict the length of the mixing zone between anthracite and sand layers. This equation was:

$$L_m = 5.47\ (D_t/D_s) - 11.36$$

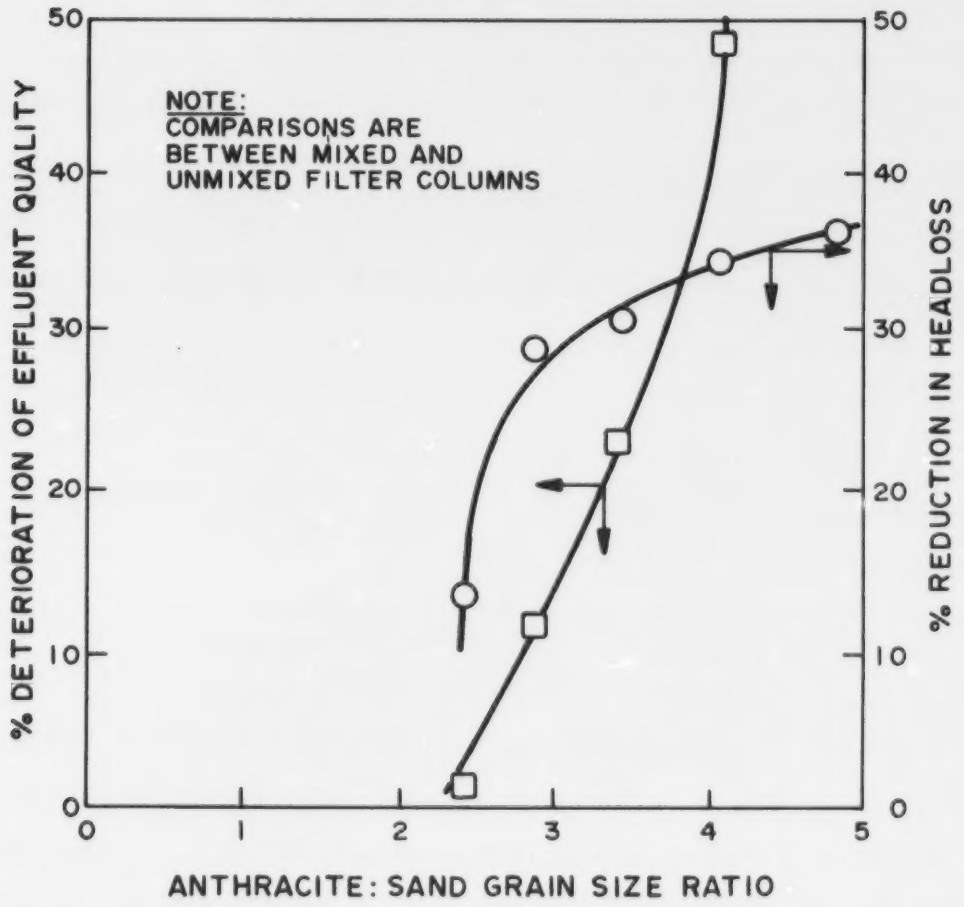
where:

L_m = mixing length; cm

D_t = anthracite diameter

D_s = sand diameter

The size ratio was 2.07 from this equation for no mixing to occur. This ratio was similar to that determined by Fair et al[44] in Table 9. Vigneswaran and Mazumdar also found that mixing of media at the interface was detrimental to effluent quality and that the best effluent quality was obtained with no intermixing. Examination of Figure 12 reveals the tradeoffs involved in choosing between improved headloss characteristics and poorer effluent quality as a function of anthracite-sand size ratios which ultimately affect the degree of intermixing.[124] In contrast, Cleasby and Sejkora[129] concluded that in filters where intermixing of media occurred, a better quality filtrate was produced than from filters which were not mixed. Other



GRAPH DEPICTING THE EFFECT OF ANTHRACITE: SAND RATIO ON EFFLUENT QUALITY AND HEADLOSS
(AFTER VIGNESWARAN & MAZUMDAR[124])

FIGURE 12

reports[130,131] tended to support Vigneswaran and Mazumdar[124] but there remains a lack of sufficient data in the literature to solve the apparent contradiction.

6.4 PERFORMANCE

The performance of multi-media filters in terms of filter run lengths, headloss, and backwashing efficiency was generally superior to that of rapid sand filters.[77,128,133] Effluent quality was comparable from rapid sand and multi-media filters.[77] The use of chemical pretreatment was considered essential by most authors particularly where direct filtration was practised.[21,133]

Removals of particles reported in the literature were similar to or better than those for rapid sand filtration.[114,134] Bryck and Walker[138] reported that a tri-media package unit with alum coagulation removed 96 to 98% of 7 to 12 μm sized particles. Westerhoff[136] reported excellent removal of particles from a multi-media filter which was consistently better than a simultaneously operated rapid sand filter (> 99% removal of particles). Filtration rates were up to 16 m/h or three times that of the rapid sand filter. Alum coagulation, flocculation, and sedimentation were the pretreatment steps.

As with rapid sand filtration, the use of filter aids to improve the performance of multi-media filters was reported.[137]

7. OTHER FILTER TECHNOLOGIES

7.1 INTRODUCTION

The scope of this technology review has been limited to potable water filtration technologies operated in a gravity, downflow mode. This covered most of the commonly used filtration processes in the water treatment industry, however there are other water filtration technologies which have not been considered but should be discussed briefly so the reader is aware of their existance and some of their operating and performance characteristics. These technologies include modifications of rapid sand filters and the use of precoat filters.

7.2 RAPID FILTER VARIATIONS

Three major types of variations of rapid filters were found:

- granular monomedia other than sand;
- altered flow regimes; and
- mobile-bed or continuous sand filters.

Romagnoli and Berglund'[4] studied the use of polyurethane foam filters as an alternative to dual-media filters. They studied wastewater effluent polishing and found superior performance using foam. Though they mentioned further studies were underway on applications to potable drinking water no subsequent reports were found in the literature.

Several investigators studied the use of monomedia anthracite filters. A paper by Uhler et al[33] suggested that an anthracite filter with an effective size of 1.5 mm and a depth of 1.2 m could outperform a 0.9 m deep, dual-media filter containing anthracite and sand having 1.1 and 0.63 mm effective sizes respectively. Particle removals were about 70% in the anthracite filter. This paper was very limited in its scope and much more data were needed to substantiate their claim. Craft[21] ranked monomedia anthracite filters second only to dual-media filtration in performance. Conley[23] observed poorer effluent quality from monomedia anthracite filters than for sand and dual-media filters. Robeck et al[33] recorded marginally better effluent turbidity using sand or coal alone rather than as a dual-media filter. No effort was made to optimize the dual-media filter. Logsdon et al[3] reported inferior performance from anthracite filters when compared to sand filters for particle removals.

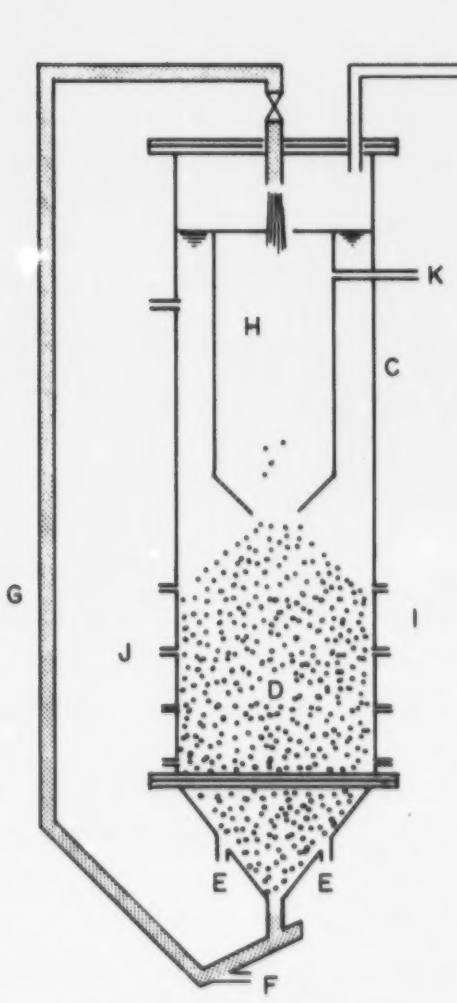
A well designed, statistically based study would demonstrate any differences in media. No such study was found.

Traditionally, gravity, downflow systems have been used for granular filtration of potable water. Pressure filters operate under the same principles as rapid sand and multi-media filters except the driving force is not gravity.[10] The most common domestic application has been in treating groundwater supplies for iron and manganese removal, swimming pool water filtration, and some surface water supplies for small communities or on-site treatment.[44,146] Their use was thought to be restricted to small applications where influent water was of high quality.[146,147]

Bryck and Walker[38] reported 88.3% removal of 7 to 15 μm sized particles at a 24.4 m/h filtration rate.

Upflow filters originated from the desire to take advantage of hydraulically graded, coarse to fine sand media.[40] Gregory et al[42] studied an upflow filter. They concluded that because of design difficulties and operating problems resulting from filter upsets, it would not be used routinely in potable water treatment. However, it had a large bed solids capacity and long filter runs were reported. They reported filtration rates of 15 m/h and an effluent turbidity of 1.0 TU. Good backwashing was necessary to maintain reliable performance. Hamann and McKinney[43] and others[44] had similar results and the process was capable of producing finished water of less than 0.1 JTU provided filter upsets were avoided. Smit[45] reported in 1963, the successful use of upflow filters in Western Europe. He quoted 200% higher flow rates and production of 500% more water per unit surface area. He provided no supporting references or performance data.

Continuous sand filters, also called radial flow or mobile-bed filters (see Figure 13), were discussed in the literature.[38,46] Allanson and Austin[46] described one type where sand was continuously wasted, washed, and replaced so that it was never taken out of service. Consequently the poor quality effluent following backwashing was avoided. No information on particle removals was presented other than total suspended solids reduction to 1.0 mg/L in wastewater treatment. Another study[47] presented results from a water treatment plant using continuous



LEGEND

A RAW WATER INLET
B FLOCCULANT
C FILTER COLUMN
D SAND BED
E EFFLUENT
F AIR INJECTION PIPE
G SAND RECYCLE TUBE
H INNER COMPARTMENT FOR SAND COLLECTION AND DISTRIBUTION
I SAMPLE TAPS
J PRESSURE TAPS
K SLUDGE REMOVAL PIPE

DETAIL OF MOBILE BED FILTER
(AFTER VIGNESWARAN ET AL[148])

FIGURE 13

sand filtration. The filter was unable to achieve 0.2 NTU in the effluent without an anionic polyelectrolyte added to the influent water. Another surface water treatment plant was described in the same paper where conventionally coagulated water filtered at 16 m/h had turbidity reduced from 6.3 NTU to less than 1.0 NTU.

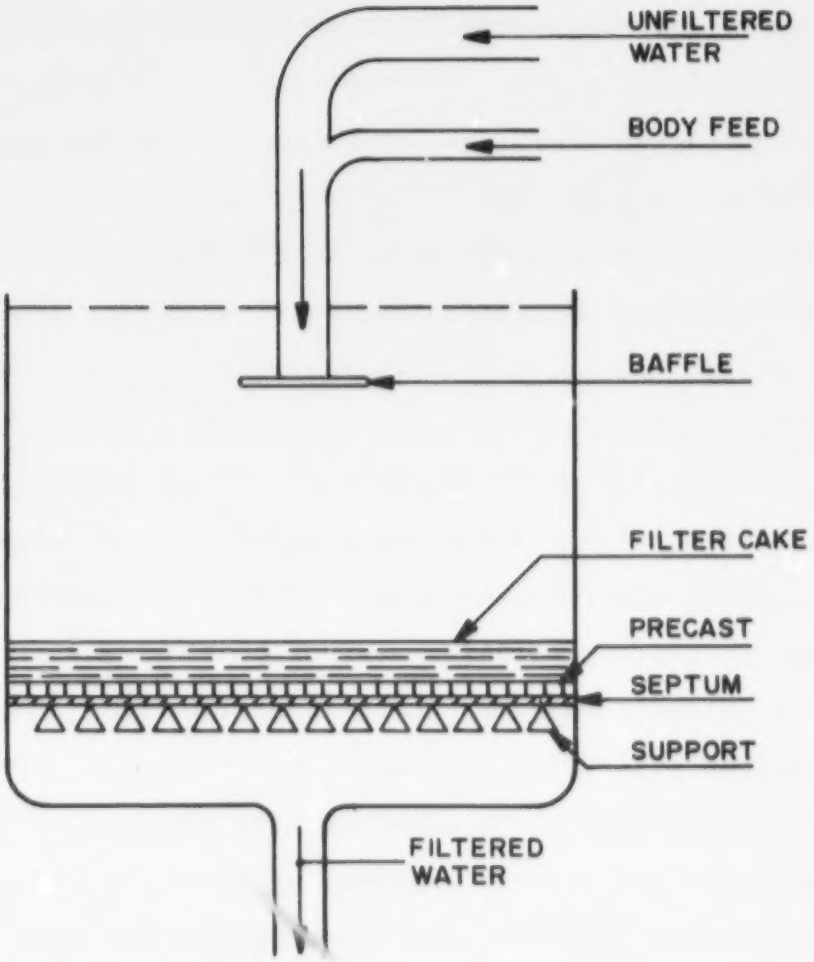
Vigneswaran et al[44,145] studied mobile-bed filters and found that filter performance was a function of the sand recycle rate. They also found that different filtration rates had different optimum sand recycle rates for the best filtrate quality. At optimum operating conditions, between 93 and 99% removals of suspended solids were possible.

It was not apparent from the literature if this variation of rapid sand filtration was capable of achieving 0.1 NTU effluent turbidity.

7.3 PRECOAT FILTERS

These filters operate by passing water through a thin layer of diatomaceous earth (DE) or man-made material supported by the septum.[44,145] Figure 14 illustrates the typical arrangement of a DE filter whether it is pressure or gravity operated. Bell[145] described the operation of a precoat, DE filter:

1. A thin layer of precoat, DE is deposited on the septum. For exceptionally clear water this may be all that is required.
2. To prevent turbid water from clogging the filter, a small amount of DE is continually added as body feed to maintain a permeable filter cake.



SCHEMATIC DIAGRAM OF DIATOMITE FILTER
(AFTER BELL[150])

FIGURE 14

3. Finally, once the headlosses across the filter cake become too great or the filter cake begins to slough, the filter is removed from service and the filter cake is removed. New precoat is applied and the cycle starts again.

Baumann et al[81] summarized the use of DE filters in municipal water treatment. Their report included an extensive bibliography of DE filtration prior to 1965 and a table of municipal installations in the United States. They concluded that although properly designed and operated DE systems could produce high quality water, more research was required in measuring operating efficiency in terms of turbidity reduction and other residues resulting from coagulation and flocculation. Dillingham and his coworkers[82,83] developed DE filtration equations to optimize DE filtration in terms of flow rate, body feed, and headloss. Effluent quality was not considered.

Lawrence[84] documented the operation of a 27 ML/d DE filtration plant in California. Unfortunately, no information was available on effluent quality as this was not considered a performance criterion. Chaudhuri et al[85] in a classic study on virus removal by DE filters found DE filters to be ineffective in removing viruses unless the filters were precoated with a cationic polyelectrolyte. Also, turbidity of the water reduced the effectiveness of the filter for virus removal. The filtration rate and type of precoat medium were thought to significantly affect the efficiency of virus removal. Arora[86] recommended the use of laboratory studies for establishing effluent quality performance criteria for each application of precoat filtration.

Recent concerns regarding waterborne Giardia lamblia have encouraged some investigators to study precoat filtration as a means of removing those particles. The experience of the United States Army in World War 2 using DE filters to remove Entamoeba histolytica[18] suggests the same process may be effective in removing similar sized particles with similar surface properties. Logsdon et al[24,17] reviewed work on E. histolytica removal by the U.S. Army. Flow rates of 0.4 to 10.6 m/h resulted in greater than 99.99% removals using DE filters. They also reported more recent results studying the removal of G. Lamblia by DE filtration. They found generally 99.9% or greater of cysts were removed but there was no correlation with turbidity. The operating conditions for these removals was 1.0 kg of precoat per m^2 of septum and a body feed of approximatly 30 mg/L. The filtration rate was 2.2 to 3.5 m/h. Operating parameters of less than these resulted in poorer removals. Precoat greater than 1.0 kg/m^2 produced no improvements in efficiency. Filter control could not be done by turbidity measurements since there was no correlation with cyst removals. They concluded that adequate precoat and body feed control were important for reliable removal of cysts. Bryck and Walker[23] evaluated DE filtration for a British Columbia community. They evaluated a package, pressure DE unit which had a 2.4 m/h filtration rate, 1 kg/m^2 precoat, and body feed of 5 to 20 mg/L. They achieved 98.8% reduction of particles in the 7.5 to 15 μm size range. Of the four filtration processes evaluated, DE filtration was the most costly.

It appears diatomite filters are capable of producing particle free water, however, other alternatives such as slow sand filtration may be more economical.

8. CONCLUSIONS

This review examined the removal of particulates from water supplies by common filtration technologies in terms of the usual design parameters and operating modes. The following conclusions were reached:

1. Pretreatment by coagulation and flocculation is necessary to obtain high particle removals in rapid sand and multi-media filters regardless of raw water quality.
2. Slow sand filters and diatomaceous earth filters were capable of consistently high particle removals without pretreatment.
3. The turbidity objective standard of 1.0 NTU is unsatisfactory for controlling filtration processes if particulate removal is desired. A goal of 0.10 NTU may be a better measure for operating purposes.
4. Turbidity and particle counts are poorly correlated. The use of turbidity measurements alone may not be adequate for monitoring filter performance when particles are of interest. Particle counting methods should be considered for performance monitoring.
5. Particle size and distribution characteristics are important in determining the performance of any filter.
6. Mathematical models and computer simulations are possibly valuable tools in process design, analysis, and operation but require calibration using pilot studies or operating data.
7. Particle removal efficiencies vary:
   a. inversely with medium grain size;
   b. inversely with the filtration rate;

c. inversely with water viscosity;

d. with influent particle size, the poorest occurring with particles approximately 1.0 μm in size;

e. directly with influent particle concentration;

f. directly with influent particle density; and

g. directly with bed depth.

8. Intermixing of media resulting from backwashing exhibits contradictory effects on the performance of multi-media filters. Some reports stated it improved performance, others that it adversely affected performance.

9. Declining rate filtration appears to produce a superior filtrate compared to constant rate operation.

10. The cleaning of filters produces a period of poor quality filtrate which can be filtered to waste. Alternatives include a "slow start" mode or a chemical addition to wash water but these are not well documented methods.

11. None of the alternate technologies reviewed appear to be technically or economically viable.

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